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PL-TR-91-2293
Environmental Research Papers, No. 1096

IMPLICATIONS OF THE KHRGIAN-MAZIN DISTRIBUTION FUNCTION FOR WATER CLOUDS AND DISTRIBUTION CONSISTENCIES WITH AEROSOLS AND RAIN

Vernon G. Plank

6 December 1991

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
6 December 1991

3. REPORT TYPE AND DATES COVERED
Scientific, from 1970 to 1991

4. TITLE AND SUBTITLE

Implications of the Khrgian-Mazin Distribution Function for Water Clouds and Distribution Consistencies with Aerosols and Rain

5. FUNDING NUMBERS

PE: 62101F
PR: 6670
TA: 12
WU: 12

6. AUTHOR(S)

Vernon G. Plank

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Phillips Laboratory (GPAA)
Hanscom AFB,
Massachusetts 01731-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

ERP, No. 1096
PL-TR-91-2293

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for Public Release, Distribution Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Applications of the Khrgian-Mazin (KM) distribution function for water clouds are discussed. The equations for the number concentration, cross-sectional area, visibility, liquid water content, and the radar/lidar reflectivity factor of water droplets are presented and modified by an assumption stemming from visibility considerations. Visibility is considered at some length and visibility theory is extended into arenas of "recognition visibility" and "discernment visibility" in both clear-air and cloudy circumstances. Radar/lidar distribution equations are presented that specify the detectability of clouds, in general and for natural cloud types, as a function of radar wavelength. A so-called "M vs Z" relation is also presented that is undoubtedly the first to be developed for water clouds. Truncation effects, primarily involving instruments that do not detect the full size extent of particle distributions, are illustrated. Relations among cloud physics quantities that are solidly tied mathematically to the KM distribution function (twenty in number) are summarized.

Composite distribution equations for aerosols plus clouds plus rain, or any combination, are described with examples of their utility.

It is concluded that the KM function for water clouds is highly versatile and useful and that the composite equations are realistic and informative.

14. SUBJECT TERMS

See reverse side

15. NUMBER OF PAGES
200

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	SAR

Item 14.

Cloud Physics
Aerosol Physics
Precipitation Physics
Visibility
- Visibility, history
- Visibility, object specific
- Visibility, recognition
- Visibility, discernment
- Visibility, limits
- Visibility, measurements

Visual Range
Radar/Lidar Meteorology
Cloud Detectabilities with radar/lidar
M vs Z Relations
Weather Definition
"Rain Erosion"
Climatology
Number Concentration of Particulates/Hydrometeors
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Preface

The AFGL cloud droplet model, based on the Khrgian-Mazin (KM) distribution function, was used for some 20 years to predict the probable cloud situations along the trajectories of missiles for "weather definition" and nose cone erosion prediction. The intimate association of the KM function with visibility theory was recognized and used to provide semi-quantitative equations. The details of the model are described in this report and visibility theory is extended considerably to define and consider different types of visibility, namely recognition and discernment visibility, the visual ranges of specific objects and the limiting conditions of maximum atmospheric seeability in clear-air and cloudy situations.

The KM function further permits predictions in the field(s) of radar/lidar meteorology. The equation that describes the distribution of the radar reflectivity factor with droplet diameter is developed, which, on integration, yields the total reflectivity factor, Z ($mm^6 m^{-3}$). A so-called M vs Z relation for water clouds is derived which is

$$M = 4.02\ Z^{0.552} \qquad g\ m^{-3},$$

where M is the cloud liquid water content in $g\ m^{-3}$. This relation, which depends strictly on the size distribution properties of the cloud droplets, enables M to be estimated from radar/lidar measurements of Z.

Actually, there are 20 relationships among cloud physics quantities that are solidly tied mathematically to the KM distribution function. All 20 have present or potential applications, which are noted.

In the AFGL weather work mentioned, it was found that cross-disciplinary problems existed between the fields of cloud physics and precipitation physics that led to mathematical discontinuities (of various important quantities) across the vague boundary zones of the separate disciplines. This led to investigations of composite distribution equations that would "smooth out" the discontinuities. These investigations are recounted and extended to include aerosols as well.

The effects of lower and upper diameter truncation on the distributed and totals equations are considered throughout and are illustrated from time to time as seems most informative. Need for such double truncation of the equations arises due to (1) natural causes, (2) the artificial restraints placed on the equations by different, disciplinary definitions and (3) the design characteristics of instruments that are being, or will be, used to provide direct measurement data.

From the work reported, it is concluded that the KM distribution function, and the other associated distribution equations of Gamma function type, provide very realistic and tremendously useful descriptors of size-distributed and totals quantities involved in cloud physics, precipitation physics, and aerosol physics.

Acknowledgements

The considerable contributions of Mr. Chankey N. Touart are acknowledged. Mr. Touart was manager of the AFGL part of the SAMS/ABRES program, and constantly insisted that the AFGL work should always be conducted to achieve the highest scientific standards.

The author thanks Mr. Robert O. Berthel for his continuing review of the developing manuscript and for the advice he provided in numerous discussions of distribution-function and visibility details. He also wishes to acknowledge the extensive contributions of Ms. Florence L. Annese whose help and advice in typing, drafting, duplicative efforts and general manuscript preparation are deeply appreciated. Without her help, this report would have been impossible.

During the later official review of the manuscript, Dr. Samuel Chang checked the basic physics and mathematics and Dr. Arnold A. Barnes, Jr. examined the manuscript in meticulous detail. Dr. Barnes, among other suggestions, programmed a variety of the basic equations for main-frame computer solution, which led to several changes in the equation constants regarding the number of significant figures that should be carried for overall consistency. For this assistance, the author is also very thankful.

Implications of the Khrgian-Mazin Distribution Function for Water Clouds and Distribution Consistencies with Aerosols and Rain

1. HISTORY AND INTRODUCTION

From 1970 to 1984, the Air Force Geophysics Laboratory (AFGL) provided weather definition information to the Ballistic Missile Office (BMO) of the Air Force Systems Command (AFSC) for their SAMS/ABRES* program of investigating the "rain erosion effects" of hydrometeors (rain, water clouds, snow, ice crystals) that were present in the atmosphere along the trajectories of missiles or re-entry vehicles. The objective was to determine the erosion effects of the hydrometeors on the nose cones of the vehicles.

Since direct measurements of the size distribution and liquid water content (LWC) of hydrometeors along the path trajectories could not be made in real time, we, at AFGL, developed two empirical models to predict the microphysical situations that were likely to occur along the trajectories. One model predicted the likely events in the precipitation size range of the hydrometeors ($100 \leq D \leq 5000$ µm, where D is the drop diameter in drizzle or rain) and the second predicted the likely events in the cloud size range of the hydrometeors ($1 \leq D \leq 100$ µm, with D being the droplet diameter in water clouds).

The first of these models, the precipitation model, has been used extensively from 1970 to the present, in Plank[1] (1977), Plank and Berthel[2] (1982), Berthel and Plank[3] (1983), Banta, Berthel, and Plank[4] (1986), and in Berthel, Banta, and Plank[5] (1987).

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* Received for Publication 2 Dec 1991

* These are acronyms for Sandia Air Force Materials Study and Advanced Ballistic Re-Entry System.

[1] Plank, V.G., 1977: *Hydrometeor Data and Analytical-theoretical Investigations Pertaining to the SAMS Missile Flights of the 1972–73 Season at Wallops Island, Virginia.* AFCRL/SAMS Report No. 5, AFGL-TR-77-0149, AD A051 192, ERP No. 603, 239 pp.

[2] Plank, V.G. and Berthel, R.O. (1982) A descriptive double-truncated exponential model for hydrometeors of precipitable size. Extended Abstracts: Conference on Cloud Physics, Nov. 15–18, 1982, Chicago, IL, preprint Vol., 190–194. AFGL-TR-82-0347, AD A122036.

[3] Berthel, R.O., and Plank, V.G. (1983) *A Model for the Estimation of Rain Distributions.* AFGL-TR-83 0030, AD A130080, ERP No. 822, 48 pp.

[4] Banta, R., Berthel, R.O., and Plank, V.G. (1986) A bulk microphysical parameterization based on doubly-truncated exponential distribution and empirical relationships. *Conference on Cloud Physics*, Snowmass, CO.

[5] Berthel, R.O., Banta, R., and Plank, V.G. (1987) *The Application of Double-truncated Hydrometeor Distributions to Numerical Cloud Models.* AFGL-TR-87-0050, ERP No. 966, ADA 185 273, 26 pp.

However, the second model, for the cloud-size range of the hydrometeors, has never been reported before, except for a brief summary by Plank[6] (1974). This model was very useful to us during the SAMS/ABRES program and it is still pertinent today, as a base reference for describing the general nature of cloud-size distributions in the atmosphere as associated with visibility theory. We have progressively upgraded and expanded the model over the years, based on the fundamental distribution function of Khrgian and Mazin (KM). This function is described in the book "Cloud Physics," by Borovikov, Gaivoronskii, Zak, Kostarev, Mazin, Minervin, Khrgian, and Shmeter[7] (1963) which summarizes and extends the work of Mazin[8] (1952), Mazin[9] (1957), Khrgian[10] (1952), Khrgian and Mazin[11] (1952), and Khrgian and Mazin[12] (1956), plus others. Future references to this work will be Khrgian/Mazin[13] (1963).

The "KM model" is highly versatile, having applications in such fields as cloud definition, atmospheric visual-range/visibility, radar and lidar meteorology, and in providng continuity/ consistency information for cloud and meso-scale "storm models."

It should be noted that once a distribution function has been specified, it then follows immediately, by rigorous physics and mathematics, that all size-distributed and total quantities (involving droplet number concentrations and total number, involving summed, projected cross-sectional areas and totals, as is important to visibility, involving cloud liquid water content (LWC), distributed and total, and involving radar and lidar reflectivities, distributed and total) have also been specified for any given single sample. This fact, that all of the quantities cited above are rigorously interrelated by the single specification of a distribution function, will be demonstrated herein.

The ability to "double truncate" distribution equations is highly valuable. Therefore, all distribution equations herein are written for truncation between lower and upper size limits of cloud droplet diameter and all "totals equations" incorporate an appropriate "truncation ratio."

This report is intended to demonstrate the versatility and utility of the KM equations across various diverse fields of endeavor, each having their own conventional units and nomenclature. To deal with the units problem, the author has specified a "standard set" of units in which all distribution and totals equations are commonly expressed. Thus, droplet diameters are in mm and the bandwidth of the distributed quantities is in mm. The latter should pose no difficulties for cloud physicists (as strictly classified) since bandwidth is merely a "scale adjust factor" that can be changed to meet any disciplinary requirement or to "match"classified data.

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[6] Plank, V.G. (1974) *Liquid-water-content and Hydrometeor Size-distribution Information for the SAMS Missile Flights of the 1971-72 Season at Wallops Island, Virginia. AFCRL/SAMS Report No. 3.* AFCRL-TR-74-0296, AD A002370, Special Report No. 178, 143 pp.

[7] Borovikov, A.M., Gaivoronskii, I.I., Zak, E.G., Kostarev, V.V., Mazin, I.P., Minervin, V.E., Khrgian A. Kh., and Shmeter, S.M. (1963) *Cloud Physics.* Israel Prog. Sci. Transl., Jerusalem, 392 pp.

[8] Mazin, I.P. (1952) Raschet otlozheniya kapel' na kruglykh tsilindricheskikh poverkhnostyakh (Calculation of droplet deposition on round cylindrical surfaces). *Trudy Tsentral Aerolog. Obsv.*, No. 7.

[9] Mazin, I.P. (1957) Fizicheskie osnovy obledeneniya samoletov (Physical bases of aircraft icing). Moscow, *Gidrometeorizdat.*

[10] Khrgian, A.Kh. (1952) Nekotorye dannye o mikrostrukture oblakov (Some data on the microstructure of clouds). *Trudy Tsentral Aerolog. Obsv.*, No. 7.

[11] Khrgian, A.Kh., and Mazin, I.P. (1952) O raspredelenii kapel' po razmeram v oblakakh (The size distribution of droplets in clouds). *Trudy Tsentral Aerolog. Obsv.*, No. 7, 56.

[12] Khrgian, A.Kh., and Mazin, I.P. (1956) Analiz sposobov kharakteristiki spektrov raspredeleniya oblachnykh kapel' (Analysis of methods of characterization of distribution spectra of cloud droplets). *Trudy Tsentral Aerolog. Obsv.*, No. 17, 36-46.

[13] Khrgian, A.Kh., and Mazin, I.P. (1963) *Cloud Physics.* Israel Prog. Sci. Transl., Jerusalem, 392 pp.

There are other quantities requiring conversion that cross disciplinary bounds or that have been used in the literature. For example, the number concentration of cloud droplets in cloud physics is conventionally expressed as number (No.) per cm^{-3}. The number concentration in precipitation physics is No. per m^3. Likewise, with regard to the density of liquid water, this is usually specified in g cm^{-3}, but, in particular theoretical developments, it is advantageous to employ g m^{-3}. There is also the problem of our "thinking units"—the British system for most Americans versus the Metric system for many others.

In any event, the units of all equations are carefully noted and the need for a change from standard are explained, if not obvious.

The sections on visibility occupy a preponderance of the report text. This is because the size distribution of cloud droplets (the KM function) is intimately related to visibility theory. There is no implication, however, that the other fields of endeavor considered are of lesser importance.

Consolidated distribution equations encompassing the full size range of aerosols, water-clouds and rain are described in Appendix A. Aspects of the Mie (1908) scattering theory that are important to equation development are presented in Appendix B. The visibility characteristics of a monodispersed population of cloud droplets, as opposed to those of the KM function, are demonstrated in Appendix C. These appendixes contain references that are included in the "List of References." A separate bibliography is also included.

The report begins with a derivation of equations.

2. DERIVATION OF EQUATIONS

2.1 Number Concentration

The size distribution properties of cloud droplets in the atmosphere can be reasonably described by the distribution function of Khrgian and Mazin[13] (1963).* This is

$$N_D = Q\, D^2\, e^{-\Omega D} \qquad (d \le D \le D_m) \qquad \text{No. } m^{-3}\, mm^{-1}\,, \tag{1}$$

where the subscript "D" signifies "distributed by diameter" and where Q (in units of mm^{-3} m^{-3}) and Ω (in units of mm^{-1}) have discrete values based on the type and liquid water content (LWC) of the clouds being considered. The equation, as applied herein, is presumed to be descriptive only between the truncation limits D = d (a minimum diameter of physical or instrumental restriction) and $D = D_m$ (a maximum diameter of physical or instrumental restriction). The units of d and D in the equation are in millimeters.

The modal (peak value) diameter of the N_D distribution is

$$D'_N = 2/\Omega \qquad mm\,. \tag{2}$$

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* The Khrgian-Mazin distribution function has also been used by Deirmendjian[14] (1964) to study the scattering and polarization of water clouds and hazes at visual and infrared wavelengths.

[13] Khrgian, A.Kh., and Mazin, I.P. (1963) *Cloud Physics*. Israel Prog. Sci. Transl., Jerusalem, 392 pp.

[14] Diermendjian, D. (1964) Scattering and polarization properties of water clouds and hazes in the visible and infrared. *Appl. Opt.* **3**:187–196

D'_N is a measurable quantity of cloud distributions, hence, when D'_N is known, Ω is also known, through Eq. (2).

The *total* number of cloud droplets in the population described by Eq. (1) is

$$N = \int_d^{D_m} N_D \, dD \qquad \text{No. m}^{-3}, \tag{3}$$

or, on performance of the integration,*

$$N = \frac{Q\,\Gamma(3)\, r_N}{\Omega^3} \qquad \text{No. m}^{-3}, \tag{4}$$

where Γ (3) is the gamma function of 3 (= 2) and r_N is a "truncation ratio" specified by

$$r_N = \frac{\displaystyle\int_d^{D_m} N_D \, dD}{\displaystyle\int_0^{\infty} N_D \, dD} \qquad \text{N.D.}, \tag{5}$$

where N.D. stands for nondimensional. From Eq. (1), this becomes

$$r_N = {}^1/_2 \{e^{-\Omega d} [(\Omega d)^2 + 2\Omega d + 2] - e^{-\Omega D_m} [(\Omega D_m)^2 + 2\,\Omega D_m + 2]\} \qquad \text{N.D.}, \tag{6}$$

with d and D_m in mm and Ω in mm^{-1}.

Another useful expression involving number concentration is the equation relating the peak value of N_D to the total number concentration N. From Eqs. (1), (2), and (4), and recognizing that $D = D'_N$ at the modal peak,

$$N_{D_p} = \frac{0.541\, N}{d'_N\, r_n} \qquad \text{No. m}^{-3}\,\text{mm}^{-1}, \tag{7}$$

which equation can also be used in reverse, if desired.

2.2 Geometric Projected Area

The geometric (or projected) cross-sectional area of the cloud droplets described by Eq. (1) is distributed with diameter as,

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* The definite integral $\int_d^{D_m} D^n e^{-\Omega D}\, dD$, where n is any integer, is described in the Handbook of Chemistry and Physics[15] (1982), (one of many references in which this integral is evaluated).

[15] Weast, R.C., and Astle, M.J., eds. (1982) *Handbook of Chemistry and Physics*, CRC Press, Inc., Boca Raton, Florida, A-63, E-202.

$$A_D = \frac{\pi D^2 N_D}{4} \quad (d \le D \le D_m) \qquad m^{-1}\,mm^{-1}\,, \tag{8}$$

or

$$A_D = \frac{\pi}{4} \times 10^{-6}\, Q\, D^4\, e^{-\Omega D} \quad (d \le D \le D_m) \qquad m^{-1}\,mm^{-1} \tag{9}$$

from Eq. (1). The constant carries length conversion units of $m^2/10^6\ mm^2 = 10^{-6}$.

The modal diameter of the A_D distribution (corresponding to the peak value) is

$$D'_A = 4/\Omega = 2\,D'_N \qquad mm, \tag{10}$$

using Eq. (2).

The *total* cross-sectional area, of all droplets of all sizes between the truncation limits $D = d$ and $D = D_m$, is

$$A = \int_d^{D_m} A_D\, dD \qquad m^{-1}\,, \tag{11}$$

which, from Eq. (9), on integration, yields

$$A = \frac{\pi \times 10^{-6}\, Q\, \Gamma(5)\, r_A}{4\,\Omega^5} \qquad m^{-1}\,, \tag{12}$$

where $\Gamma(5)$ is the gamma function of 5 (= 24) and r_A, in analogy with Eq. 5, is the truncation ratio for cross sectional area given by

$$\begin{aligned} r_A = {}^1/_{24}\, \{ & e^{-\Omega d}\, [(\Omega d)^4 + 4(\Omega d)^3 + 12(\Omega d)^2 + 24\,\Omega d + 24] \\ & - e^{-\Omega D_m}[(\Omega D_m)^4 + 4(\Omega D_m)^3 + 12(\Omega D_m)^2 + 24\,\Omega D_m + 24]\} \qquad \text{N.D.} \end{aligned} \tag{13}$$

It might be mentioned at this point that it is advantageous, computationally and for ease of writing, to express the equations for *all* truncation ratios herein in terms of Ω, rather than D'_N, through Eq. (2).

From Eqs. (2), (9), (10), and (12), and noting that $D = D'_A$ at the modal peak,

$$A_{D_p} = \frac{0.391\, A}{D'_N\, r_A} \qquad m^{-1}\,mm^{-1} \tag{14}$$

which equation also applies in reverse.

2.3 Liquid Water Content

The liquid water content of the cloud droplets described by Eq. (1) is distributed with diameter as

$$M_D = \frac{\pi D^3 \rho_W N_D}{6} \qquad (d \le D \le D_m) \qquad g\ m^{-3}\ mm^{-1}\ , \tag{15}$$

or, from Eq. (1), and since ρ_W, the density of liquid water, equals 1 g cm^{-3},

$$M_D = \frac{\pi \times 10^{-3}\ Q\ D^5 e^{-\Omega D}}{6} \qquad (d \le D \le D_m) \qquad g\ m^{-3}\ mm^{-1}\ , \tag{16}$$

where the constant carries length conversion units of $cm^3/10^3\ mm^3 = 10^{-3}$.

The modal diameter of the M_D distribution is

$$D'_M = 5/\Omega = 2.5\ D'_N \qquad mm\ , \tag{17}$$

employing Eq. (2).

The *total* LWC of all cloud drops of the population is

$$M = \int_d^{D_m} M_D\, dD \quad g\ m^{-3}\ , \tag{18}$$

which, from Eq. (16), on integration, gives

$$M = \frac{\pi \times 10^{-3}\ Q\ \Gamma(6)\ r_M}{6\ \Omega^6} \qquad g\ m^{-3}\ , \tag{19}$$

where $\Gamma(6)$ is the gamma function of 6 (= 120) and r_M, in analogy with Eq. (5), is the truncation ratio for liquid water content specified by

$$\begin{aligned} r_M = {}^1/_{120} \{ & e^{-\Omega d} [(\Omega d)^5 + 5(\Omega d)^4 + 20(\Omega d)^3 + 60(\Omega d)^2 + 120\Omega d + 120] \\ & - e^{-\Omega D_m} [(\Omega D_m)^5 + 5(\Omega D_m)^4 + 20(\Omega D_m)^3 + 60(\Omega D_m)^2 + 120\Omega D_m + 120] \} \qquad \text{N.D.}\ . \end{aligned} \tag{20}$$

From Eqs. (2), (16), (17), and (19), with $D = D'_m$ at the modal peak,

$$M_{Dp} = \frac{0.351\ M}{D'_N\ r_M} \qquad g\ m^{-3}\ mm^{-1} \tag{21}$$

which may be reversed, if pertinent.

2.4 Radar/Lidar Reflectivity Factor

The distributed values of the radar/lidar reflectivity factor Z for the cloud droplets described by Eq. (1) are expressed by

$$Z_D = D^6 N_D \quad (d \le D \le D_m) \quad mm^6\ m^{-3}\ mm^{-1}\ , \tag{22}$$

or, from Eq. (1),

$$Z_D = Q\ D^8 e^{-\Omega D} \quad (d \le D \le D_m) \quad mm^6\ m^{-3}\ mm^{-1}\ . \tag{23}$$

The modal diameter of the Z_D distribution is

$$D'_Z = 8/\Omega = 4\ D'_N \quad m\ , \tag{24}$$

using Eq. (2).

The *total* reflectivity factor for any given cloud population is

$$Z = \int_d^{D_m} Z_D\ dD \quad mm^6\ m^{-3}\ , \tag{25}$$

which, from Eq. (23), results in

$$Z = \frac{Q\ \Gamma(9)\ r_Z}{\Omega^9} \quad mm^6\ m^{-3}\ , \tag{26}$$

where $\Gamma(9)$ is the gamma function of 9 (= 40,320) and r_Z is a truncation ratio for the reflectivity factor, which, in analogy with Eq. (5), yields

$$\begin{aligned} r_Z = {}^1/_{40,320}\ \{ & e^{-\Omega d}\ [(\Omega d)^8 + 8(\Omega d)^7 + 56(\Omega d)^6 + 336(\Omega d)^5 + 1680(\Omega d)^4 + 6720(\Omega d)^3 \\ & + 20160(\Omega d)^2 + 40320\Omega d + 40320] - e^{-\Omega D_m}[(\Omega D_m)^8 + 8(\Omega D_m)^7 + 56(\Omega D_m)^6 + 336(\Omega D_m)^5 \\ & + 1680(\Omega D_m)^4 + 6720(\Omega D_m)^3 + 20160(\Omega D_m)^2 + 40320\Omega D_m + 40320]\} \quad N.D.\ . \end{aligned} \tag{27}$$

Although Eq. (27) is "messy," it can be readily solved by computer or even by a programmable hand calculator.

From Eqs. (2), (23), (24), and (26), with $D = D'_Z$ at the modal peak,

$$Z_{Dp} = \frac{0.279\ Z}{D'_N\ r_Z} \quad mm^6\ m^{-3}\ mm^{-1} \tag{28}$$

which also applies in reverse.

3. THE DISTRIBUTION AND TOTALS EQUATIONS EXPRESSED IN TERMS OF D'_N AND M

3.1 The Equation for Q in Terms of D'_N and M

The equation for Q is obtained from Eq. (19). If this equation is solved for Q,

$$Q = \frac{6\Omega^6 M}{10^{-3} \pi \Gamma(6) r_M} \quad mm^{-3} m^{-3} , \tag{29}$$

or, on evaluation of the numerical factors,

$$Q = \frac{15.9 \Omega^6 M}{r_M} \quad mm^{-3} m^{-3} . \tag{30}$$

This equation may be expressed in terms of D'_N and M through the use of Eq. (2). Thus,

$$Q = \frac{1020 M}{D'^6_N r_M} \quad mm^{-3} m^{-3} , \tag{31}$$

which is the desired equation.

3.2 The Distribution and Totals Equations

With the development of Eq. (31), it becomes possible to express the distributed and totals equations (1), (2), (9), (12), (16), (19), (23), and (26) in terms of the measurable quantities D'_N and M.

To avoid unnecessary verbiage, the converted forms of the equations cited are merely listed below without comment. The conversions require the use of Eq. (31) and also the use of Eq. (2). The numerical quantities have been evaluated and all constants have been rounded off to three or four significant figures as is appropriate.

N_D and N versus D'_N and M

$$N_D = \frac{1020 M D^2 e^{-2 D/D'_N}}{D'^6_N r_M} \qquad (d \le D \le D_m) \qquad No.\ m^{-3} mm^{-1} . \tag{32}$$

$$N = \frac{255 M r_N}{D'^3_N r_M} \qquad No.\ m^{-3} . \tag{33}$$

A_D and A versus D'_N and M

$$A_D = \frac{8.0 \times 10^{-4} M D^4 e^{-2 D/D'_N}}{D'^6_N r_M} \qquad (d \le D \le D_m) \qquad m^{-1} mm^{-1} . \tag{34}$$

$$A = \frac{6.0 \times 10^{-4}\, M\, r_A}{D'_N\, r_M} \qquad m^{-1}. \tag{35}$$

M_D versus D'_N and M

$$M_D = \frac{0.534\, M\, D^5\, e^{-2\,D/D'_N}}{D'^6_N\, r_M} \qquad (d \le D \le D_m) \qquad g\ m^{-3}\ mm^{-1}. \tag{36}$$

Total M is, of course, one of the measured, independent quantities.

Z_D and Z versus D'_N and M

$$Z_D = \frac{1020\, M\, D^8\, e^{-2\,D/D'_N}}{D'^6_N\, r_M} \qquad (d \le D \le D_m) \qquad mm^6\ m^{-3}\ mm^{-1}. \tag{37}$$

$$Z = \frac{8.03 \times 10^4\, M\, D'^3_N\, r_Z}{r_M} \qquad mm^6\ m^{-3}. \tag{38}$$

4. DISTRIBUTION PLOTS AND ILLUSTRATIONS OF TRUNCATION EFFECTS

Plots of the distribution equations (32), (34), (36), and (37) are presented in Figure 1. The upper diagram shows three plots of distributed droplet number concentration, for liquid water content values of 1.0, 0.5, and 0.1 g m^{-3}, which are indicated on the diagram. Also indicated are the values of the total number concentration, as computed from Eq. (33). D'_N is assumed to have a typical, constant value of 0.01 mm = 10 μm and the vertical line of this diameter is noted [Eq. (7)]. Two sets of ordinate and abscissa scales are employed. The normal set, at the left and bottom, gives N_D in No. cm^{-3} μm^{-1} versus D in μm (cloud physics convention). The auxiliary set, at the right and top, gives N_D in No. m^{-3} mm^{-1} versus D in mm (precipitation physics convention).

The diagram (second from top in Figure 1) contains three plots of the distributed, cross-sectional areas of the cloud droplets for the M values cited above, as computed from Eq. (34). The values of the total, projected cross-sectional area, for all droplets of each population depicted, as computed from Eq. (35), are noted on the plots, as is the vertical modal line of $D'_A = 2\ D'_N = 20\ \mu$m [Eq. (10)]. Values of $\forall$ are also noted. This maximum visibility quantity is discussed in Sections 6.1 and 6.2.

The third and fourth diagrams of Figure 1 are essentially similar to the first two. The third shows plots of M_D, from Eq. (36), and the total M values are those of basic specification. The line of $D'_M = 2.5\ D'_N = 25\ \mu$m is indicated [Eq. (17)]. In the fourth diagram, the plots are those of Eq.

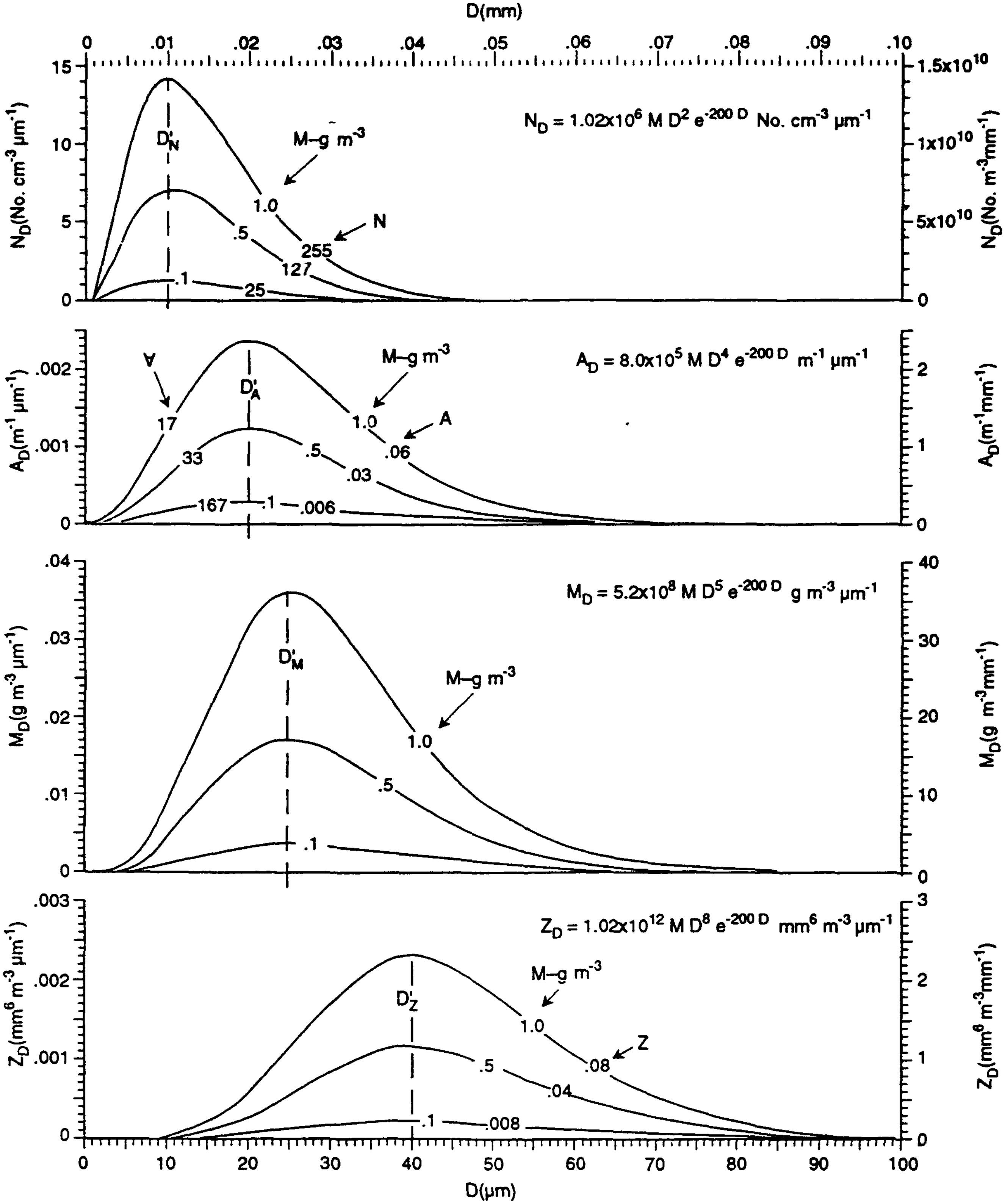

Figure 1. Non-truncated plots of N_D, A_D, M_D and Z_D for three liquid water content (LWC) values.

(37); the total reflectivity values come from Eq. (38). The modal diameter of Z_D is $D'_Z = 4\ D'_N = 40$ μm [Eq. (24)].

It is assumed that there is no truncation in the Figure 1 plots, hence $r_N = r_A = r_M = r_Z = 1.0$. It should also be noted that the distribution equations shown on the diagrams require D entry in mm.

The four diagrams of Figure 1 reveal the shape of the curves of the N_D, A_D, M_D, and Z_D distributions and the ordinate scales provide numerical information about the values versus droplet diameter. A comparison of diagrams demonstrates how the modal peaks "shift upward" from N_{D_p} to A_{D_p} to M_{D_p} to Z_{D_p} (where the "p" subscript signifies "peak," or maximum, value). This upward shift of the peak is in accord with the increase of the "diameter moment" (of a Gamma Function), from D^2, for N_D, to D^4, for A_D, to D^5, for M_D, and to D^8, for Z_D.

Figure 1 is also useful as a reference for illustrating the effects of truncation on the four distributions. Two cases of truncation will be considered, both involving commercially-available, aircraft instruments.

The Johnson-Williams (JW) instrument is representative of a class of cloud LWC sensors referred to as "hot wire devices."* A length of thin copper wire, encased in teflon tubing, is exposed perpendicular to the airstream and electrically heated. This heated wire comprises one arm of a balanced bridge. A second, similar wire, not heated and exposed parallel to the airstream, comprises an adjacent, reference arm of the bridge. Water droplets striking the encased, heated wire are evaporated, thus cooling the wire and decreasing its resistance. The degree of unbalance of the bridge is a function of the cloud LWC.

From flight experience, the JW instrument is generally capable of measuring droplet diameters between the truncation limits $d \cong 1\ \mu$m to $D \cong 40\ \mu$m, with educated guesses extending the latter to something approaching 80 μm.

The JW instrument truncation, relative to the KM distributions, is illustrated in Figure 2. The figure is merely a modification of Figure 1, with screening superimposed to indicate the spectral portions of the plots that would not be detected by the JW. It is seen (upper diagram) that the instrument would obtain sufficient information to define the distribution characteristics of droplet number concentration and to ascertain a fairly accurate estimate of total number concentration. The truncation ratio for the detected portion of the plots is $r_N = 0.985$, from Eq. (6). This agrees, as it should, with the visually discernable ratio of the white areas under the curves to the areas covered by the screening.**

The detection ability of the JW instrument for cloud droplets that are important to projected cross-sectional area (and visual range) is not quite as good as for number concentration. The second diagram of Figure 2 shows that the large diameter parts of the A_D distributions are appreciably truncated. The truncation ratio, r_A, for the plots is 0.901, from Eq. (13). This means that the JW detects 90 percent of the total projected area that is present in the KM distributions, which conforms with the ratio of white to screened areas shown visually.

* Bacharach Instrument Co., 625 Alpha Dr., RIDC Ind. Pk., Pittsburgh, PA 15238

** Since the diagram plots are "linear plots," areas under the curves on the paper are directly proportional to the totals, or truncated portions, of the distributed quantities lying under the curves.

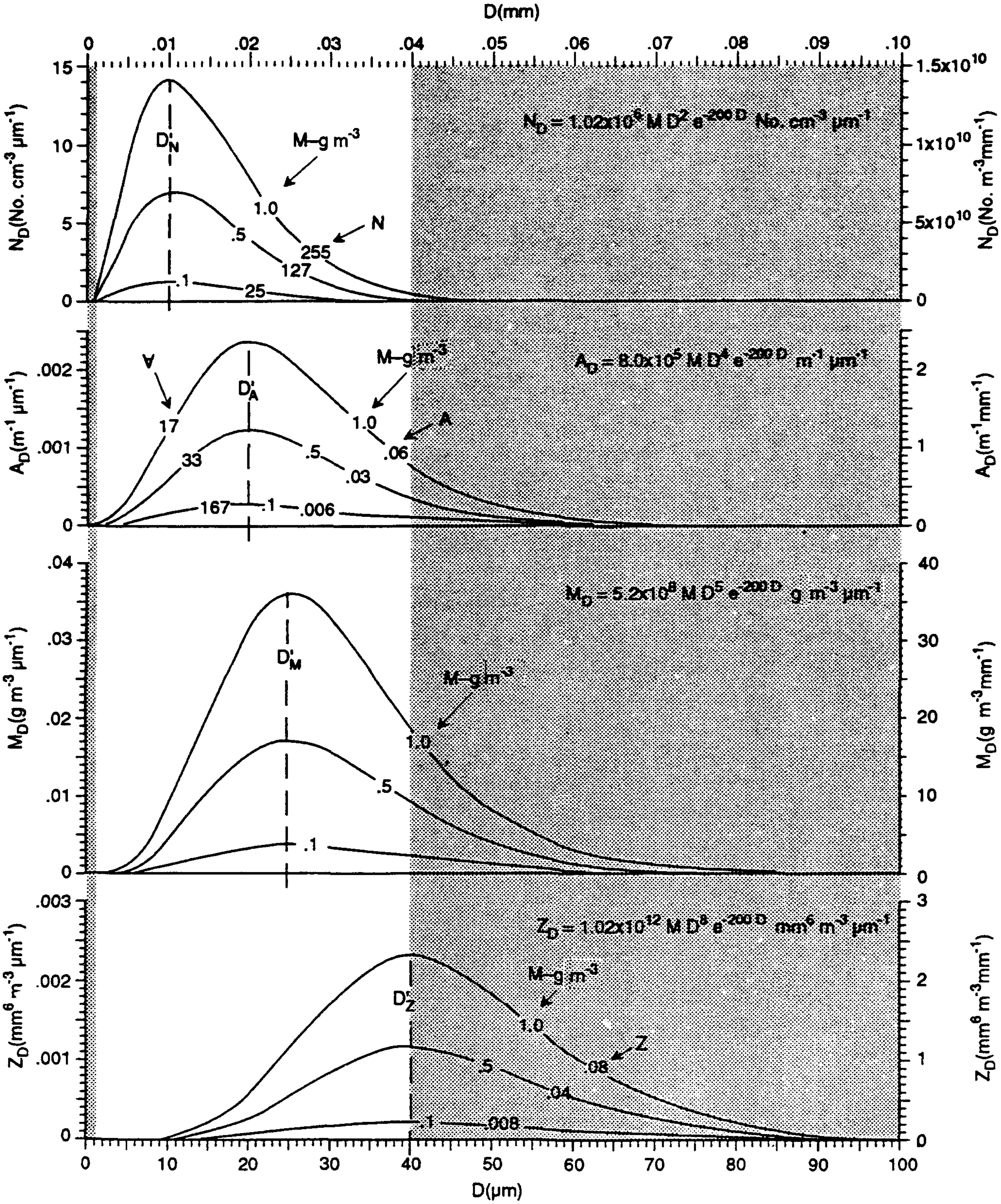

Figure 2. Plots of N_D, A_D, M_D and Z_D as truncated by the JW-cloud-LWC instrument, for three LWC values.

The third diagram of the figure reveals the JW instrument truncation situation for liquid water content. The truncation ratio, from Eq. (20), is $r_M = 0.809$, which implies that the JW instrument's detection ability for cloud droplets that are important to LWC is about 81 percent.

The fourth diagram of the figure demonstrates that the JW instrument fails to detect the majority of the cloud droplets that are important to the radar reflectivity factor. Only some 41 percent of the droplets are detectable, from the r_Z value (0.407) of Eq. (27). This suggests that the JW instrument is unsuitable for studies of the radar reflectivity properties of water clouds. [For any, given, distributed quantity, the author considers an instrument to be incapable of providing useful information about the quantity if (1) the instrument cannot detect the normally-anticipated modal peak within its truncation range, or, if (2) the truncation ratios anticipated are ≤ 0.5.]

In contrast to truncation involving the JW sensor, let us now focus on another class of commercially-available, aircraft, cloud-LWC-instruments, namely the Particle Measuring Systems (PMS)* so-called one-dimensional cloud probe (1DC) and two-dimensional cloud probe (2DC), which are described by Knollenberg[16] (1970). Several models exist for each of the probes. These instruments essentially consist of a line of photodiode detectors that are laser illuminated across an air gap oriented normal to the airstream. Cloud and drizzle droplets that pass across the "gap line" shadow one or more of the detectors. When the diode information (as being "shadowed or not") is suitably buffered and recorded for semi-immediate release, number count data are provided as a function of droplet diameter. This is the 1DC instrument. The 2DC instrument differs in that knowledge of the true airspeed of the aircraft is employed to "look at" the droplets (or ice crystals) individually, in two dimensions. This provides "shadow graphs" of the particles encountered. Total LWC with either instrument is obtained by summation.

The PMS, 1DC, and 2DC probes are commonly truncated at $d = 20\ \mu m$, which is the smallest diameter of detectability. The largest diameter detectable with the 1DC instruments is $300\ \mu m$. The largest detectable with the 2DC's ranges from $600\ \mu m$ to $2000\ \mu m$ dependent on the model type.

The truncation situation of the PMS sensors is illustrated in Figure 3. The figure is a modification of Figure 1 and is similar to Figure 2, in that screening has been used to indicate the diagram portions not detectable by the instruments. Thus, $d = 20\ \mu m$ and $D_m \geq 200\ \mu m$, which lies well beyond the right hand boundaries of the figure diagrams.

The truncation situation for number concentration indicates that the PMS instruments are unsuitable for cloud studies involving this quantity. The truncation ratio from Eq. 6 is $r_N = 0.238$ and it is visually obvious, from the plots, that the instruments fail to detect the modal peaks of the KM distributions.

The situation for projected, cross-sectional area is somewhat questionable; $r_A = 0.629$ and it is seen that the modal peaks are detected, but "just barely." The instruments cannot be used for area/visibility studies *unless* their data are "compensated" for the spectral portions "not seen."

The truncation situation for LWC is improved, but data compensation is still required. The truncation ratio is 0.785. The situation for radar reflectivity factor is good; $r_Z = 0.979$ and the

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* Particle Measuring Systems, 1855 South 57th Court, Boulder, Colorado 80301

[16] Knollenberg, R.G. (1970) The optical array: an alternative to scattering or extinction for airborne particle size determination. *J. Appl. Meteor.*, **9**:86–103.

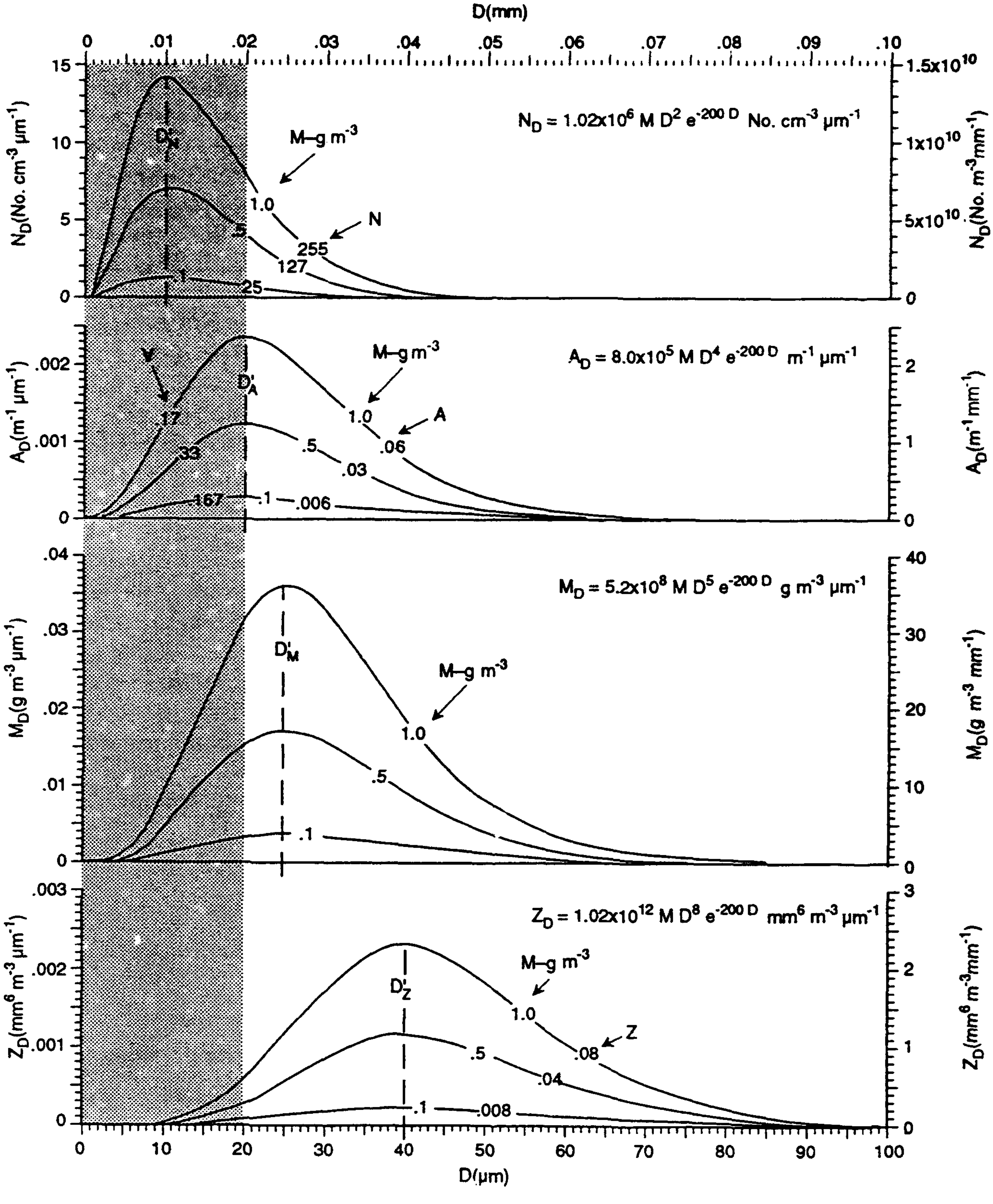

Figure 3. Plots of N_D, A_D, M_D and Z_D, as truncated by the PMS-cloud-LWC instruments, for three LWC values, reference text.

instruments should provide excellent information about the radar reflectivities in water clouds. (For those radars that are capable of detecting clouds, see Section 10.3 and Table 8.)

5. THE BASIC KHRGIAN-MAZIN DISTRIBUTION FUNCTION

The KM distribution function is the equation (for number concentration) that leads to all the other distribution and totals equations developed herein. Therefore, we have a legitimate question in asking, "how descriptive of the real world of cloud physics is the function, actually?".

The general form of the function, as pointed out by Diermendjian[14] (1964), is

$$G_D = F\,D^n\,e^{fD}, \tag{39}$$

where G_D is any given distributed-hydrometeor-quantity, D is the effective diameter(s) of the hydrometeors, n is an integer "moment number" (of a Gamma Function), F is a coefficient factor, not necessarily a constant, and f is a multiplication factor of the exponent, also not required to be constant.

Khrgian and Mazin were probably the first to recognize the importance of this generalized distribution form as applied specifically to cloud physics. They tested the form versus some 600,000 droplet samples of number concentration and concluded that the best description was obtained for a moment number n = 2, [Borovikov, et. al.[7] (1963)]. This leads directly to their distribution function, Eq. (1) herein.

Diermendjian himself presented powerful evidence about the descriptivity of the general equation. He applied the equation to aerosols, employing the data of Junge, Chagnon and Manson[17] (1961). He found that the data were best described by the moment number 6.* He then used the theory of Mie[18] (1908), together with his equation for aerosols and that of KM for water clouds, to deduce the scattering and polarization properties of aerosols, hazes and water clouds at visual and infrared wavelengths. His report is a valuable contribution to the literature.

There should be little question, therefore, about the quality of the KM function that provides the basis for the present work.

The primary, immediate areas of application of the KM function would appear to lie (1) in the area of "weather definition" and (2) in the area of providing design, operational, and testing assistance to insure the internal cloud physics consistency and continuity of so-called "storm models."

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* The skewing of the general distribution function, [Eq. (39)], toward larger sizes relative to the mode, increases with moment number. Diermendjian, from Khrgian-Mazin, noted that the number distributions for clouds is best fitted with moment number 2 (small skew). As the moment number increases to 4 (for plan area), to 5 (for LWC), to 8 (for radar Z), the skew of the associated distributions increases. Diermendjian also found that the number distribution for aerosols is best fitted with moment number 6. This implies immediately that, for aerosols, the moment for plan area is 8, the moment for LWC is 9 and the moment for radar Z is 12. Thus, the aerosol distributions evidence more skewing than the cloud distributions.

[14] Diermendjian, D. (1964) Scattering and polarization properties of water clouds and hazes in the visible and infrared. *Appl. Opt.* **3**:187–196

[7] Borovikov, A.M., Gaivoronskii, I.I., Zak, E.G., Kostarev, V.V., Mazin, I.P., Minervin, V.E., Khrgian A. Kh., and Shmeter, S.M. (1963) *Cloud Physics.* Israel Prog. Sci. Transl., Jerusalem, 392 pp.

[17] Junge, Ch.E., Chagnon, C.W., and Manson, J.E. (1961) *J Meteor.*, **18**:81.

[18] Mie, G. (1908) Beiträge zur optik trüber medien, speziell kolloidaler metallosungen. *Ann. Phys.*, **25**:377–445 (Leipzig).

Weather definition comprises a wide range of application which can be roughly described as "the ability to predict the state of the atmosphere, including hydrometeors, for any operational need." As mentioned, AFGL provided such information to BMO as part of their SAMS/ABRES program concerning hydrometeor erosion of the nose cones of missiles and re-entry vehicles. The hydrometeors were predicted using the KM function, for water clouds, from aircraft JW measurements of cloud LWC[6] (Plank, 1974) and using the exponential function described by Plank[1] (1977) and Plank, Berthel and Barnes[19] (1980), for rain, employing radar data. Ice crystals and snow were also predicted from radar data. The equations contributed importantly to the assessment of hydrometeor erosion of nose cones at hypersonic velocities.

The capabilities of AFGL [now Geophysics Directorate of the Phillips Laboratory (GP)] for predicting the distribution properties of water clouds should be enhanced by the equations developed herein. With the consolidated equations for both clouds and rain, presented in Appendix A, if they are programmed for computer solution, much of the previous work of providing tabular and graphical information to a user could be substantially reduced and the products could be submitted more quickly.

The second area of application is that of providing design, operation, and testing information for storm models. A start toward this goal has been reported by Banta, Berthel and Plank[4] (1986) and Berthel, Banta and Plank[5] (1987). In essence, the KM equations, incorporated into the composite equations, will provide checks on the consistency of the various microphysical assumptions that were made in the original design of the model. For example, is an assumption regarding the production of liquid water in the model consistent with another assumption made elsewhere in the model about the distributed nature(s) of the hydrometeor spectra of the totals? Is there continuity in the working model? Questions such as these are reintroduced in Appendix A, after the discussion and illustration of the features of the composite equations.

We turn now to a consideration of visual range and visibility, as predicted by the KM distribution function.

6. DESCRIPTION OF VISUAL RANGE, MAXIMUM VISIBILITY, AND VISIBILITY

Bennett[20] (1935) was probably the first to note the distinction between "visibility," a subjective, popular-usage term, and the "visual range," a term that is more specific and quantifiable.

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[6] Plank, V.G. (1974) *Liquid-water-content and Hydrometeor Size-distribution Information for the SAMS Missile Flights of the 1971–72 Season at Wallops Island, Virginia. AFCRL/SAMS Report No. 3.* AFCRL-TR-74-0296, AD A002370, Special Report No. 178, 143 pp.

[1] Plank, V.G. (1977) Hydrometeor Data and Analytical-theoretical Investigations Pertaining to the SAMS Missile Flights of the 1972–73 Season at Wallops Island, Virginia. AFCRL/SAMS Report No. 5, AFGL-TR-77-0149, AD A051 192, ERP No. 603, 239 pp.

[19] Plank, V.G., Berthel, R.O., and Barnes, A.A. (1980) An improved method for obtaining water content values of ice hydrometeors from aircraft and radar data. *J. Appl. Meteorol.*, **19**,1293–1299, AFGL-TR-81-0011, AD A094328.

[4] Banta, R., Berthel, R.O., and Plank, V.G. (1986) A bulk microphysical parameterization based on doubly-truncated exponential distribution and empirical relationships. *Conference on Cloud Physics*, Snowmass, CO.

[5] Berthel, R.O., Banta, R., and Plank, V.G. (1987) *The Application of Double-truncated Hydrometeor Distributions to Numerical Cloud Models.* AFGL-TR-87-0050, ERP No. 966, ADA 185 273, 26 pp.

[20] Bennett, M.G. (1935) Further conclusions concerning visibility by day and night. *Quart. J. Roy. Meteorol. Soc.*, **61**:179–188.

Middleton[21] (1941) and Houghton[22] (1945) added additional details to the distinction.

To paraphrase Huschke[23] (1959), the term "visibility" is specified to be the distance at which viewed objects can be *recognized*. The more general expression "visual range" carries no requirement of recognition but only of the ability to "see" out to a given range. For example, an aircraft pilot flying in clouds always has the day/night ability to see ahead to the visual range (of "first discernment") without the also necessity that a particular object exists ahead at a visibility (distance) of "recognition."

6.1 Maximum Visibility

The maximum visibility (of "recognition") is related to the summed projected cross-sectional area of the cloud droplets in the manner illustrated and described in the following paragraphs.

Consider a square tunnel of 1 meter by 1 meter cross-section, along which "distance marks" have been emplaced every meter of length, leading to infinity (see the sketch of Figure 4). The tunnel consists of a series of cubes, each of 1 m^2 cross section and 1 m^3 volume within which there is strict mathematical adherence to the rules of the KM distribution function concerning the numbers and size distribution of cloud droplets.

If we look down this tunnel from its near end, our ability to recognize objects (that might be present at some location along the tunnel) depends on the summed, projected cross-sectional areas of the droplets. Thus, the visibility reduction due to the presence of the droplets is

$$A \forall = 1.0 \qquad \text{N.D.}\,, \tag{40}$$

or

$$\forall = 1/A \qquad \text{m}\,, \tag{41}$$

where $\forall$ is the symbol used to identify this particular quantity. The rationale for the symbol is that it is an inverted A, which is precisely correct.

For the A value of the Khrgian-Mazin distribution function, [Eq. (35)], this visibility becomes

$$\forall = \frac{1667\, D'_N\, r_M}{M\, r_A} \qquad \text{m}\,. \tag{42}$$

It is reiterated that $\forall$ describes only that portion of the visibility reduction due to the direct blocking (or shadowing) of the cloud droplets themselves. There are other important contributions to visibility reduction, such as diffraction-reflection (and the secondary effects), the contrast of the objects viewed, solar effects, the size of objects, etc. These will be considered in the following sections.

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[21] Middleton, W.E.K. (1941) *Visibility in Meteorology*, second edition, Univ. of Toronto Press, Toronto.

[22] Houghton, H.G. (1945) *Visibility. Handbook of Meteorology*. McGraw-Hill Publishers, 242–251.

[23] Huschke, R.E. (1959) *Glossary of Meteorology*. Amer. Meteor. Soc., Boston, 613.

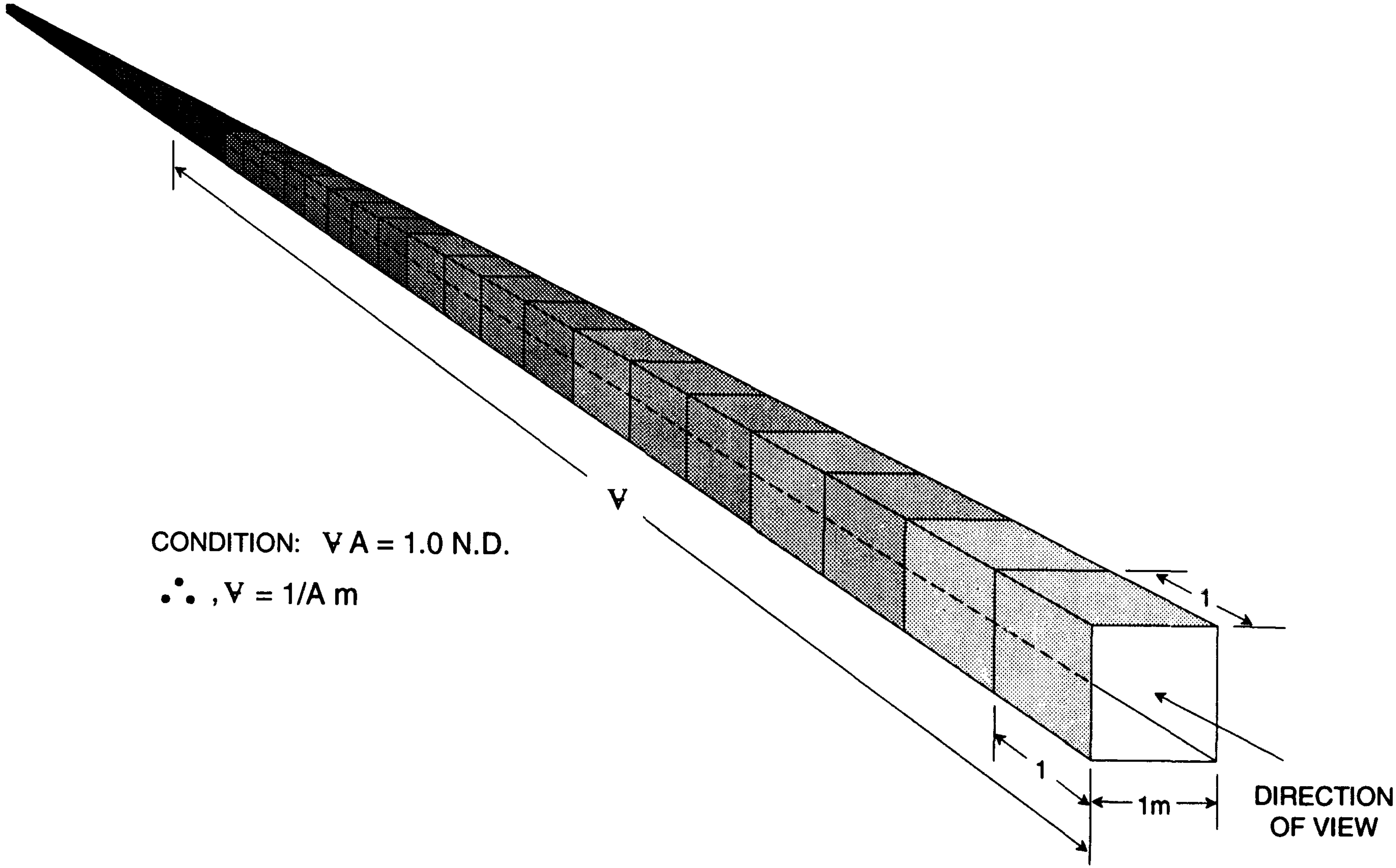

Figure 4. Sketch of the tunnel of recognition visibility.

It should be stated initially that the equations to be developed herein have no fundamental day/night dependence. They can be applied to either. In the discussions of the present report, sufficient threshold illumination (equal to or exceeding twilight amount) is assumed to exist. For nighttime viewing (not discussed herein) the equations *can be modified* to reflect the situation of looking at lights and artificially-illuminated objects.

It is also assumed a-priori that the atmospheric medium along the "path of view" in any given visibility situation is a homogeneous one and that the path(s) are not restricted by any effects of earth curvature.

6.2 Visibility

In the development of the visibility equation, it should first be noted—the details are described and illustrated in Appendix B—that cloud droplets, due to their sizes relative to the wavelength(s) of visible light, fall primarily in the region of geometric optics of the general scattering theory of Mie[18] (1908). In this region, the principal effects that tend to make the apparent diameters of the droplets "look larger" than their actual physical sizes are extinction effects caused by diffraction (σ_d), by internal reflection and refraction (σ_{rr}), by the sun's elevation and azimuth angles relative to an observer's line of sight (σ_{sol}), by secondary effects of all types (σ_{scd}) and by the backscatter toward the observer caused by atmospheric gases and aerosols that tend to reduce an observer's contrast for objects viewed (σ_{ctr}). The latter is a subject discussed by Duntley[24] (1948).

Johnson[25] (1954) has indicated that the total extinction for clouds may be written as the sum of the components. Thus,

$$\sigma = A + \sigma_d + \sigma_{rr} + \sigma_{sol} + \sigma_{scd} + \sigma_{ctr} \qquad m^{-1} , \tag{43}$$

where A, the projected, cross-sectional area, is the principal, mathematically-stable component of the total.

For simplification, Eq. (43) may be written as

$$\sigma = A + \sigma_E \qquad m^{-1} \tag{44}$$

where σ_E, the "extra extinction" caused by all components additional to A, is given by

$$\sigma_E = \sigma_d + \sigma_{rr} + \sigma_{sol} + \sigma_{scd} + \sigma_{ctr} \qquad m^{-1} , \tag{45}$$

The ratio,

$$k_\sigma = \frac{\sigma}{A} \quad \text{N.D.} \tag{46}$$

[18] Mie, G. (1908) Beiträge zur optik trüber medien, speziell kolloidaler metallosungen. *Ann. Phys.*, **25**:377–445 (Leipzig).

[24] Duntley, S.Q. (1948) The visibility of distant objects. *J. Opt. Soc. Amer.*, **38**:237–249.

[25] Johnson, J.C. (1954) *Physical Meteorology*. New York Technical Press, MIT and Wiley. 393.

has been defined by Stratton[26] (1941), Kerr and Goldstein[27] (1951) and others. It is the same ratio which, for single spheres, is illustrated in Figure B1, Appendix B, in the context of the Mie scattering theory. The ratio, of course, also applies to multiple spheres, if their size distribution is known or specified.

With Eq. (44) introduced into Eq. (46),

$$k_\sigma = \frac{A + \sigma_E}{A} = 1 + \frac{\sigma_E}{A} \quad \text{N.D.}, \tag{47}$$

which shows that, for spheres consisting of water droplets in the Mie scattering region of geometric optics, k_σ can never have a value smaller than unity.

Johnson[25] (loc. cit., page 80) has shown (working through differences of symbology) that

$$\sigma = \frac{\ln(1/\epsilon)}{V} \quad m^{-1}, \tag{48}$$

where V is the visibility and ln (1/ϵ) is the "contrast" that specifies observer or instrument ability to differentiate and "see" objects of various shades of gray, or of color, against their gray or colored backgrounds. Examples would include a black object against a white background, or vice versa, or a blue object against a reddish sky, or vice versa.

If Eq. (46) is introduced into Eq. (48) and the result is solved for V,

$$V = \frac{\ln(1/\epsilon)}{k_\sigma A} \quad m, \tag{49}$$

This is the general form of the visibility equation of Trabert[28] (1901). The equation can be made "distribution specific" with assumed (or measured) knowledge of A, based on the particular properties of the cloud droplet distribution.

For the Khrgian-Mazin distribution employed in this report, A is given by Eq. (35). When this equation is substituted in Eq. (49),

$$V = \frac{1667\, D'_N \ln(1/\epsilon)\, r_M}{k_\sigma M r_A} \quad m. \tag{50}$$

This is the *Khrgian-Mazin form of the general Trabert equation.*

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[26] Stratton, J.A. (1941) *Electromagnetic Theory*. McGraw-Hill, 563 pp.

[27] Kerr, D.E., and Goldstein, H. (1951) Radar targets and echoes, *Propagation of Short Radio Waves*, **13**, Chap. 6, McGraw-Hill.

[25] Johnson, J.C. (1954) *Physical Meteorology*. New York Technical Press, MIT and Wiley, 393.

[28] Trabert, Wilhelm (1901) Die extinction des lichtes in einem truben medium (Schweite in wolken). *Meteor. Z.*, **18**:518–525.

Equation (42) permits Eq. (50) to be written alternately as

$$V = \frac{\forall \ln (1/\epsilon)}{k_\sigma} \quad m . \tag{51}$$

The definition of maximum recognition visibility (for the KM distribution) may be determined from Eqs. (50) and (51), as follows.

The maximum occurs when $\forall = 1$ and $k_\sigma = 1.0$. For these conditions, Eq. (51) becomes

$$\ln (1/\epsilon_{max}) = 1.0 \quad N.D. , \tag{52}$$

or

$$\epsilon_{max} = 0.368 \quad N.D. . \tag{53}$$

As a matter of interest and to facilitate forthcoming comparisons with the historical work of others, we might also determine the equation conditions that apply to the KM distributions for the limit of discernment seeing.

Koschmieder[29, 30] (1924a, 1924b), from experiments and reference to the work of Weber[31] (1916), Helmholtz[32] (1896) and others, deduced that the discernment limit (for his "black body") had the value $\epsilon_0 = 0.02$, with $\ln (1/\epsilon_0) = 3.91$. Subsequent investigators almost universally used this limit as the "standard" for their visibility studies.

The seeing differences associated with recognition-viewing (or visibility) as opposed to discernment-viewing (or visual range) may be determined by writing the ratio

$$R_{D/R} = \frac{V_D}{V} \quad N.D. , \tag{54}$$

where V_D and V are the viewing limits corresponding to the discernment (V_D) and recognition (V) situations.

From Eq. (50), assuming that $\epsilon_0 = 0.02$, for discernment viewing, and $\epsilon_{max} = 0.368$, for recognition viewing, we obtain, when Eq. (50) for the separate situations is introduced into Eq. (54),

$$R_{D/R} = \frac{\ln (1/0.02)}{\ln (1/0.368)} = 3.91 \quad N.D. \tag{55}$$

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29 Koschmieder, H. (1924) Theorie der horizontalen sichtweite. *Beiträge zur physik der freien atmosphäre*, **XII**:33–53.

30 Koschmieder, H. (1924b) Theorie der horizontalen sichtweite II: kontrast und sichtweite. *Beitrage zur physik der freien atmosphare*, **XII**:171–181.

31 Weber, L. (1916) Die albedo des luft planktons. *Ann. d. Physk.* **15**:427-449.

32 Helmholtz, H.L.F. von (1896) *Handbuch der Physiologischen Optik*. Hamburg und Leipzig.

Thus, all other conditions being equal, that is, the conditions of contrast, of scattering ratio, and of LWC, the *visual range* will be 3.91 times larger than the *visibility*. This is the prediction of the KM distribution equations. The ratio value also presumes that the Koschmieder ϵ_0 value is definitive.

We continue with further consideration of the properties and limitations of the KM visibility equation, [Eq. (50)].

First of all, the truncation ratios, r_M and r_A, that enter the equation are neglected for the moment. However, they are not forgotten.

The extinction ratio, k_{σ}, of the equation should have values ranging from about 1.5 (normal) to perhaps as much as 4.0 (with solar effects). Looking at the components of Eq. (44), which establish the values of k_{σ} through Eq. (46), we should be able to evaluate the component σ_d from diffraction theory. The component, σ_{sol}, due to solar angle is also diffractive, will be of major importance, and will have maxima both in the sun direction, where coronas are observed, and in the anti-solar direction, where glories are observed. This component, too, should be amenable to evaluation from diffraction theory and from the theories of coronas and glories. According to Minnaert[33] (Dover Publications, 1954) such corona/glory phenomena are commonly present in all clouds, even though the coronas and glories themselves may not be visually obvious [also reference Jones and Condit[34] (1948)]. The components σ_{rr}, σ_{scd} and σ_{ctr} of Eq. (44) are and will be exceedingly difficult to predict. Perhaps outdoor visibility experiments under known conditions of solar angle and subject contrast might assist. Or, long-term visibility experience at numerous reporting stations might provide some useful information.

The contrast, ln $(1/\epsilon)$, in Eq. (50), for recognition viewing, will have values ranging from the maximum value of 1.0 (for ϵ_t = 0.368) to the "no contrast" value of zero.

The modal diameter, D'_N, in Eq. (49), has heretofore been assumed to be a constant, having a typical value of 0.01 mm (10 μm). This is not likely though, because, as the liquid water content decreases in a cloud, to the point where it can no longer be called a cloud, the cloud droplets at the modal peak of the size distribution *cannot* remain at constant diameter. The modal diameter (along with the rest of the distribution) must shift downward in size toward zero as the cloud LWC approaches zero. Therefore, D'_N, in Eq. (50), *must* be a function of M. The nature of the function will be explored in the continuing discussion.

6.3 Nomographic Illustration of the Characteristics of the KM Visibility Equation for Constant D'_N

For D'_N = constant = 0.01 mm and $r_M = r_A$ = 1.0 (no truncation), Eq. (49) reduces to

$$V = \frac{16.7 \ln (1/\epsilon)}{k_{\sigma} M} \quad \mathrm{m}\,, \qquad (56)$$

which is an equation in four variables, ϵ, k_{σ}, M, and V.

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[33] Minnaert, M.G.J. (1935) *Light and Colour in the Open Air*. G. Bell & Sons, Ltd. (Republished 1954, Dover Publications).

[34] Jones, L.A., and Condit, H.R. (1948) Sunlight and skylight as determinants of photographic exposure—luminous density as determined by solar altitude and atmospheric conditions. *J. Opt. Soc. of Amer.*, **38**:123.

The only way to illustrate the characteristics of this equation is by use of a nomogram. Such a nomogram is presented in Figure 5 and may be explained as follows.

The Figure 5 nomogram, in addition to indicating the solution of Eq. (56) for recognition visibility, also contains input arows and tracing lines to show, for one particular example, how a user would "enter" the nomogram with the variables k_σ, ϵ (actually [ln $(1/\epsilon)$], and M to obtain values of V.* A consideration of this example will provide instruction about the use of the nomogram.

The lower portion of the nomogram, with the insert arrows $[\ln(1/\epsilon)]_E$—"E" for "example"— and k_{σ_E} and the sloping tracing lines, partially solves Eq. (56) for the ratio $[\ln(1/\epsilon)/k_\sigma]_E$. The scale of this ratio lies along the line X - X'. The scale values are not shown on the nomogram, but the scale is linear and the values are readily deduced.

The main, upper portion of the nomogram thus receives the input quantities $[\ln(1/\epsilon)/k_\sigma]_E$, from its lower, abscissa scale, and M_E, from its left-hand ordinate scale, which solves Eq. (56) for V_E. The isolines of V have been drafted on the nomogram. With reference to these isolines, our example provides a visibility value of $V_E \cong 550$ m.

The value of $\epsilon_{max} = 0.368$ (vertical line), corresponding to perfect contrast, is noted on the nomogram, along the ϵ scale at the bottom. This vertical line may also be scaled for values of the maximum visibility, $\forall$, as indicated by the "$\forall$ arrow" at the top of the nomogram. The $\forall$ values are those of the V isolines, at the points where they intersect the vertical line. The values are the visibility reductions caused by the droplets themselves, with perfect object contrast and $k_\sigma = 1.0$.

The nomogram is limited by cloud physics and meteorological realities. Hence, M is limited, at its upper bound, at 5 g m^{-3}. Findings reported by Lewis[35] (1947), Pettit[36] (1955), and Borovikov, et al.[7] (1963) reveal that cloud LWCs rarely, if ever, exceed 2–4 g m^{-3}, so this provides a degree of "overplot." The visibility isolines are labeled from 2 m to 50,000 m (31 miles). This spans the range of research/experimental, aviation and synoptic-meteorological interest.

The Figure 5 nomogram reveals two things of fundamental importance to cloud physics and visibility. First, where visibility is concerned, *very* small values of LWC are important. Second, the dichotomy is revealed regarding the assumption of D'_N = constant. How can it be possible, for example, to have a modal diameter of 0.01 mm (10 μm) in association with a large visibility of, say 50,000 m, corresponding to M values in the range 3×10^{-4} g m^{-3} or smaller? The answer is that it is not possible. A "merger assumption," between the number concentration and mass contents of aerosols and those of water clouds, is obviously required. The assumption will necessarily involve a statement of the dependence of D'_N on M as D'_N approaches the aerosol region.

Such an assumption is described in the following section. It is a *major* assumption that will affect *all* of the subsequent work of the present report and that the author did not make lightly.

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* Real or postulated knowledge of any three of the variables will provide an estimate of the fourth (by "working the nomogram backward").

[35] Lewis, W. (1947) *A Flight Investigation of the Meteorological Conditions Conducive to the Formation of Ice on Airplanes.* Tech. Notes Nat. Adv. Comm. Aero., Wash., 1393. 34.

[36] Pettit, K.G. (1955) The characteristics of supercooled clouds during Canadian icing experiments. *Proc. Toronto Conference.*

[7] Borovikov, A.M., Gaivoronskii, I.I., Zak, E.G., Kostarev, V.V., Mazin, I.P., Minervin, V.E., Khrgian A. Kh., and Shmeter, S.M. (1963) *Cloud Physics.* Israel Prog. Sci. Transl., Jerusalem, 392 pp.

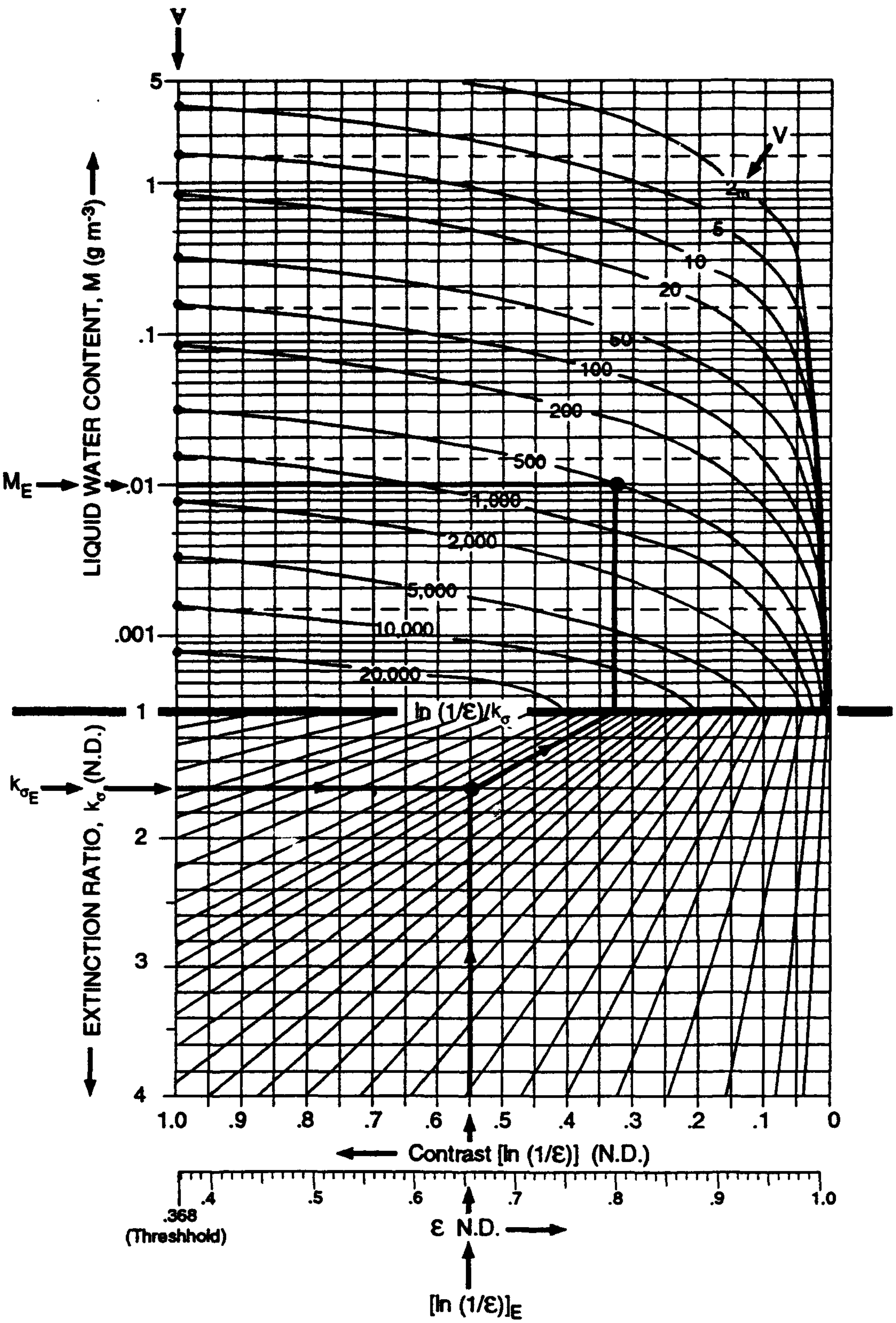

Figure 5. Nomogram for recognition visibility with isolines in meters (D'_N = constant = .01 mm), also example of nomogram use, reference text.

Rather, much of the visibility, cloud physics, and aerosol information of the literature, pertinent to the problem and cited in the references and bibliography herein, was reviewed and judged (subjectively, of course) before the assumption was made.*

7. THE D'_N VERSUS M ASSUMPTION STEMMING FROM VISIBILITY CONSIDERATIONS

The droplet sizes in cloud populations will not decrease to actual *zero* as the LWC decreases. Rather, they will decrease to the sizes of the condensation nuclei (moist aerosols) from which the clouds were first formed.

A convenient reference atmosphere for aerosols is the "dry rural model" of Fenn, et al[37] (1985). This model describes the normal, typical concentration of aerosols in the absence of any special generation sources of particulates, such as sea salt, dust, smoke and industrial pollutants. The features of the model as portrayed by the distribution function of Diermendjian[14] (1964) are illustrated in Appendix A, Figures A1–A5. Size distribution information for water clouds and rain is also presented. It is seen that the largest of the aerosols overlap the smallest cloud droplets, that the total number concentration of aerosols is about 10^5 times larger than the numbers for clouds but that the mass concentrations of aerosols is about a hundred times *smaller* than those for clouds.

In synoptic meteorology, the rule for reporting visibility as restricted or unrestricted is that visibilities smaller than 6 miles (9650 m) are considered restricted whereas those larger than 6 miles are unrestricted. Restricted is not the same as the "unlimited" specification, which occurs at a visibility equal to or greater than about 30 miles (some 48,300 m).

In making the assumption about the D'_N dependence on M, the author reasoned as follows. At an M value of 1.0 g m^{-3}, the corresponding value of D'_N is typically equal to .01 mm (10 μm). This becomes one "tie point" of the assumption. At the restricted/unrestricted boundary of visibility classification in synoptic meteorology, one wishes to define a diameter size for D'_N that is consistent with the number concentration of the larger aerosols of the atmosphere and that is also reasonably consistent, at the "unlimited boundary," with D'_N being neither "ridiculously large" or "ridiculously small," relative to the aerosol distribution. With these considerations in mind, it was presumed that $D'_N = 0.001$ mm (1 μm) at a maximum visibility, $\forall$, of 6 miles. This became the second "tie point" of the basic assumption. Also, it is a point that should be amenable to experimental verification.

The relation of D'_N and M was postulated to be of the power function form,

$$D'_N = a\, m^b \quad \text{mm}\,. \tag{57}$$

* For example, some of the major works (in the approximate chronological order of first publication) are those of Bouguer, Brewster, Tyndall, Clausius, Rayleigh, Helmholtz, Conrad, [19th Century], Trabert, Mie, Wegener, Cabannes, Ramon, Koschmieder, Ångstrom, Rozenberg, and Köhler, [1900–1930], Middleton, Junge, Houghton, Penndorf, Bricard; Levin, van de Hulst, Duntley, Shifron, Neiburger, Aufm Kampe, and Khrgian, [1930–1960], and Diermendjian, Young, Beard, Nussenzveig, Bohren, Fenn, Crane, Squires, and Warner, [1960–1990].

[37] Fenn, R.W., Clough, S.A., Gallery, W.O., Good, R.W., Kneizys, F.X., Mill, J.D., Rothman, L.S., Shettle, E.P., and Volz, F.E. (1985) Optical and Infrared Properties of the Atmosphere. Chap. 18 in *Handbook of Geophysics and the Space Environment*, Jursa, A.S., Ed., AFGL, 1-80, ADA 167000.

[14] Diermendjian, D. (1964) Scattering and polarization properties of water clouds and hazes in the visible and infrared. *Appl. Opt.* **3**:187–196

For the first "tie point," described above, the coefficient, a, of Eq. (57) becomes, a = 0.01 mm. For the second "tie point," $D'_N = 0.001$ mm when $\forall = 9650$ m (6 miles), the corresponding M value, from Eq. (50), ignoring truncation, is

$$M = 1.73 \times 10^{-4} \quad \text{g m}^{-3}, \tag{58}$$

which, when we take the natural logarithm of Eq. (57) and use the M value of Eq. (58), with D'_N = 0.001 mm, yields b = 0.27, as rounded off to two places consistent with the lack of quantitative measurements.*

For these a and b values, Eq. (57) becomes

$$D'_N = 0.01\ M^{0.27} \quad \text{mm}, \tag{59}$$

which is the author's basic assumption of relationship.

8. CONSEQUENCES OF THE ASSUMPTION

The assumption of Eq. (59) affects *all* of the distribution and totals equations of Khrgian and Mazin that have been developed thus far. Hence, before continuing our visibility discussion, we will pause to modify Eqs. (7), (14), (21), (28), and (32) through (38) for conformance with the new assumption. As before, the equations will be converted "as a batch," without comment.

Thus, with Eq. (59) substituted into these cited equations, the modified versions become, in sequence,

N_D, D'_N, N, and N_{D_p} versus M

$$N_D = 1.02 \times 10^{15}\ M^{-0.62}\ D^2 e^{-200 D M^{-0.27}} \quad (d \le D \le D_m) \qquad \text{No. m}^{-3}\ \text{mm}^{-1}. \tag{60}$$

$$D'_N = .01\ M^{0.27} \qquad \text{mm}. \tag{61}$$

(basic visibility assumption)

$$N = \frac{2.55 \times 10^8\ M^{0.19}\ r_N}{r_M} \qquad \text{No. m}^{-3}. \tag{62}$$

$$N_{D_p} = 1.38 \times 10^{10}\ M^{-0.08} \qquad \text{No. m}^{-3}\ \text{mm}^{-1}. \tag{63}$$

* The exponent "b" of Eq. (57) is very sensitive in separating situations of "sense" from those of "nonsense." Descriptive sense seemingly lies within the range b = 0.27 ± 0.02.

A_D, D'_A, A, and A_{D_p} versus M

$$A_D = 8 \times 10^8\ M^{-0.62}\ D^4\ e^{-200\ D\ M^{-0.27}} \qquad (d \le D \le D_m) \qquad m^{-1}\ mm^{-1}\ . \tag{64}$$

$$D'_A = 2\ D'_N = 0.02\ M^{0.27} \qquad mm\ . \tag{65}$$

$$A = \frac{0.060\ M^{0.73}\ r_A}{r_M} \qquad m^{-1}\ . \tag{66}$$

$$A_{D_p} = 2.34\ M^{0.46} \qquad m^{-1}\ mm^{-1}\ . \tag{67}$$

M_D, D'_M, and M_{D_p} versus M

$$M_D = 5.34 \times 10^{11}\ M^{-0.62}\ D^5\ e^{-200\ D\ M^{-0.27}} \qquad (d \le D \le D_m) \qquad g\ m^{-3}\ mm^{-}1\ . \tag{68}$$

$$D'_M = 2.5\ D'_N = 0.025\ M^{0.27} \qquad mm\ . \tag{69}$$

M is the measured, independent quantity.

$$M_{D_p} = 35.1\ M^{0.73} \qquad g\ m^{-3}\ mm^{-1}\ . \tag{70}$$

Z_D, D'_Z, Z and Z_{D_p} versus M

$$Z_D = 1.02 \times 10^{15}\ M^{-0.62}\ D^8\ e^{-200\ D\ M^{-0.27}} \qquad (d \le D \le D_m) \qquad mm^6\ m^{-3}\ mm^{-1}\ . \tag{71}$$

$$D'_Z = 4\ D'_N = 0.04\ M^{0.27} \qquad mm\ . \tag{72}$$

$$Z = \frac{0.0803\ M^{1.81}\ r_Z}{r_M} \qquad mm^6\ m^{-3}\ . \tag{73}$$

$$Z_{D_p} = 2.23\ M^{1.54} \qquad mm^6\ m^{-3}\ mm^{-1}\ . \tag{74}$$

An illustration of the above distribution and totals equations for N_D and N, A_D and A, M_D and M, and Z_D and Z is provided in Figure 6. The diagrams of the figure are similar to those of Figure 1. The same values of M are used for the individual distribution plots and the plots are for the condition of no truncation. The isolines of the modal peaks, D'_A, D'_M, and D'_Z are indicated by the dashed lines (D'_N is not included, since it would confuse the upper plot). As in Figure 1, two sets of abscissa and ordinate scales are shown, with D in μm (bottom) or mm (top) and the values of the distributed quantities in μm bandwidth (left) or mm bandwidth (right). Additionally, for N_D and N, the values are per cm^3 volume (left) or per m^3 volume (right). The distribution equations shown, it should be noted, require D entry in mm.

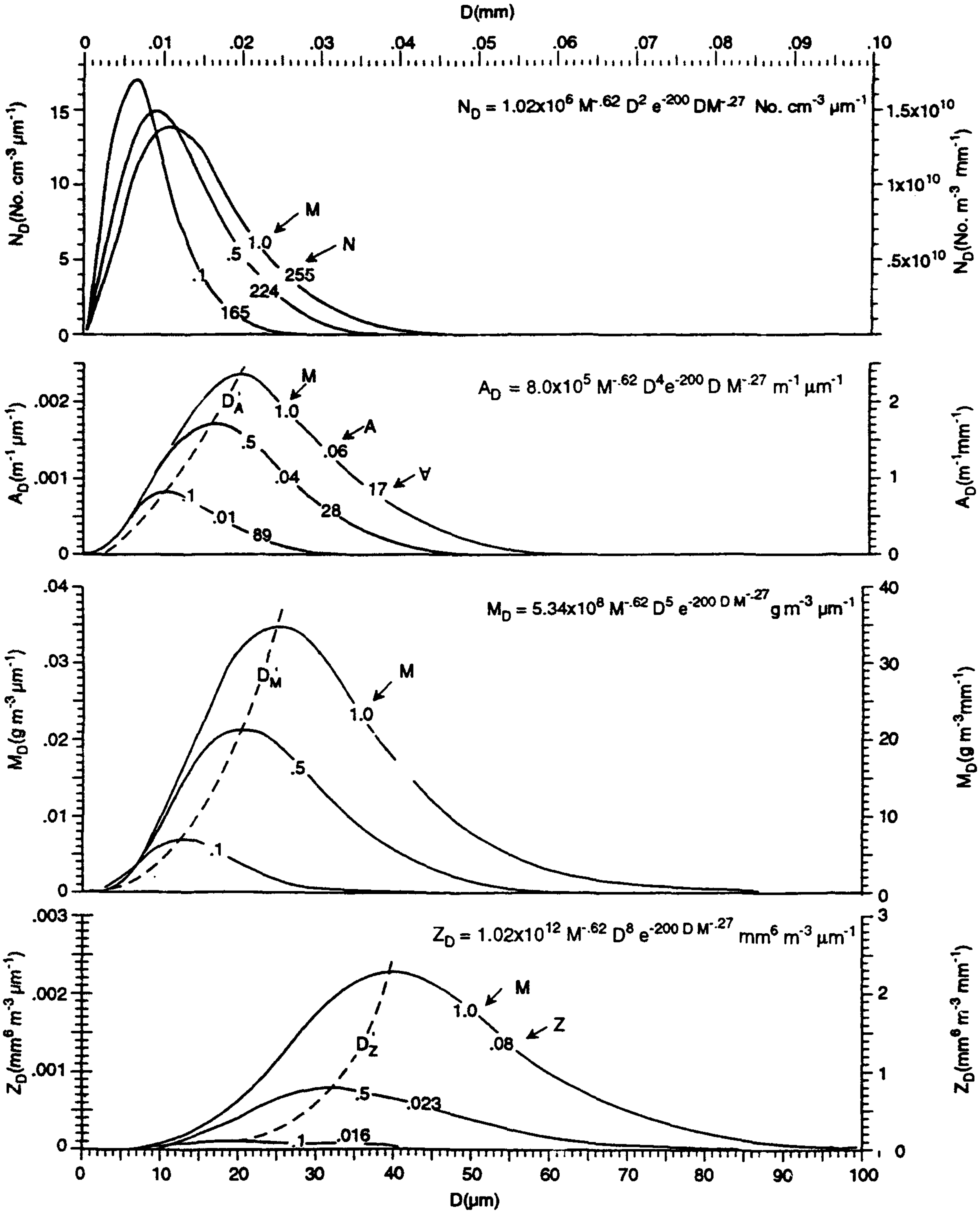

Figure 6. Plots of N_D, A_D, M_D, and Z_D for the new visibility assumption of Eq. (59), for three liquid water content values

A comparison of Figures 1 and 6 reveals the following about the new D'_N assumption relative to the previous.

With regard to number concentration (upper diagrams). the modal peaks of N_D are observed to shift to the left and increase value with decreases in LWC. This reflects the fact that the modal peak of the cloud droplets is rising to merge with the peak of the number of aerosols (condensation nuclei), which are considerably more numerous in the atmosphere than are the cloud droplets, [see Figure A1]. Another, auxiliary reason for the rising modal trend with decreasing D'_N is that, for a given value of LWC, more small droplets are required to produce the peak than are large droplets.

The modal peaks of the distribution of projected, cross-sectional area (second diagrams), shift leftward, toward D = 0, and downward, with decreasing D'_A. Also, except for the M = 1.0 g m^{-3} curves (which are common for both Figure 1 and Figure 6), the total A values are larger for the new assumption, than for the previous, and the maximum visibilities, ∀, are correspondingly smaller.

There is little to say about the M_D and Z_D distributions of the lower diagrams other than that the modes progressively move downward toward zero with decreasing LWC, as for A_D. However, the total Z values are smaller than previous, *unlike* the A values.

With respect to the truncation situations for cloud physics instruments that were illustrated in Figures 2 and 3, it is seen from Figure 6, in analogy, that "hot wire type" instruments tend to be "more attractive" for measurements under the new conditions portrayed. Conversely, the PMS, 1DC, and 2DC instruments tend to be "less attractive."*

9. VISIBILITY RECONSIDERED

The basic assumption of Eq. (59) affects the previous visibility equations as follows.

From Eq. (50), the Khrgian-Mazin form of the general Trabert equation for recognition visibility becomes

$$V = \frac{16.67\ M^{0.73} \ln(1/\epsilon)\ r_M}{k_\sigma\ r_A} \quad m \tag{75}$$

and the equation for maximum visibility becomes

$$\forall = \frac{16.67\ M^{-0.73}\ r_M}{r_A} \quad m\ , \tag{76}$$

from Eq. (51).

* It will be noted that the author has made no prior reference to the PMS, SSSP and FSSP cloud instruments, also commercially available. These instruments, which operate on the principles of the side and forward scattering of light caused to impinge on the cloud droplets (or ice crystals), are subject to many of the very same diffractive and scattering effects that, in visibility studies particularly, we are attempting to determine. Thus, the instruments are of questionable value in a comparative study such as the present.

9.1 Descriptive Nomograms and Examples of Common Visibility Experience

A nomogram illustrating the solution of Eq. (75) is presented in Figure 7. The nomogram is similar to that of Figure 5, except that no scale of ϵ is included at the bottom. Truncation is ignored, as before. A vertical scale of D'_N (*in* μm) has also been drafted in Figure 7, to the left of the M scale. The D'_N values indicated are of interest but they do not directly enter the nomographic solution of Eq. (75). The instructions for the use of the nomogram are the same as explained previously, relative to Figure 5.

This nomogram reveals the improved description of visibility resulting from the incorporation of Eq. (59). The D'_N values are in reasonable accord with gradual merging of cloud droplet distributions into the size distributions of aerosol particles (also with a merging of mass contents). The $\forall$ values along the M scale, which as in Figure 5, are the values indicated on the V isolines, conform with Eq. (76). For common M and contrast values, it is seen that the visibilities of Figure 7 are appreciably smaller than those of Figure 5. Moreover, the visibility isolines are "shaped differently" for increasing values of contrast.

The Figure 7 nomogram also reveals that very-small visibilities, of 2 m or so, are realized only under the "absolute worst' of seeing conditions, in which the LWCs are large, the extinction ratio is large, (as when looking in the direction of the sun), and the contrast between viewed objects and background is small. On the other hand, large visibilities occur with small LWC, with small extinction ratio, like looking cross sun, and with good contrast conditions for objects viewed.

For the convenience of aviation and synoptic-meteorological interests, a companion nomogram to Figure 7 is provided in Figure 8, in which the visibility isolines are scaled in feet and miles. The threshold boundaries defined as "restricted" and "unlimited" are emphasized and labeled "R6" and "U30." A third isoline is also emphasized, labeled "D2000." This is the " decision range" (important in aviation meteorology) at which an aircraft pilot, attempting to land under IFR conditions at a Category II airport (the most common) must decide whether to make the attempt, or not.*

The two nomograms just cited describe the situation of recognition visibility, which involves the ability to recognize objects seen. It is equally important to describe the situation of discernment visibility, which involves the "first discernment" of objects seen vaguely and dimly at the limits of human visual ability.

As demonstrated in Section 6.2, Eqs. (54) and (55), discernment viewing for the KM distribution function is 3.91 times larger than recognition viewing under comparable contrast conditions. Thus, the equation for discernment visibility becomes

$$V_D = \frac{65.3\ M^{-0.73} \ln(1/\epsilon)\ r_M}{k_\sigma\ r_A} \quad m\ , \tag{77}$$

from Eq. (75), and the equation for the maximum visual range becomes

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* The decision range for IFR (Instrument Flight Rules) approach to a Category II airport is governed by the pertinent FAR's (Federal Aviation Regulations), IFR §91.116h, IFR §91.189c and Appendix A, Paragraph 3, Sub-Parts 2 (iv) and 4. The trigonometry and length unit conversions required to convert these rules into terms of "decision range" are the authors' own. The range distance is "rounded off" to the nearest 100 feet. The above rules are conveniently provided in the AOPA (Aircraft Owners' and Pilots' Association) publication entitled "AOPA's Aviation USA."

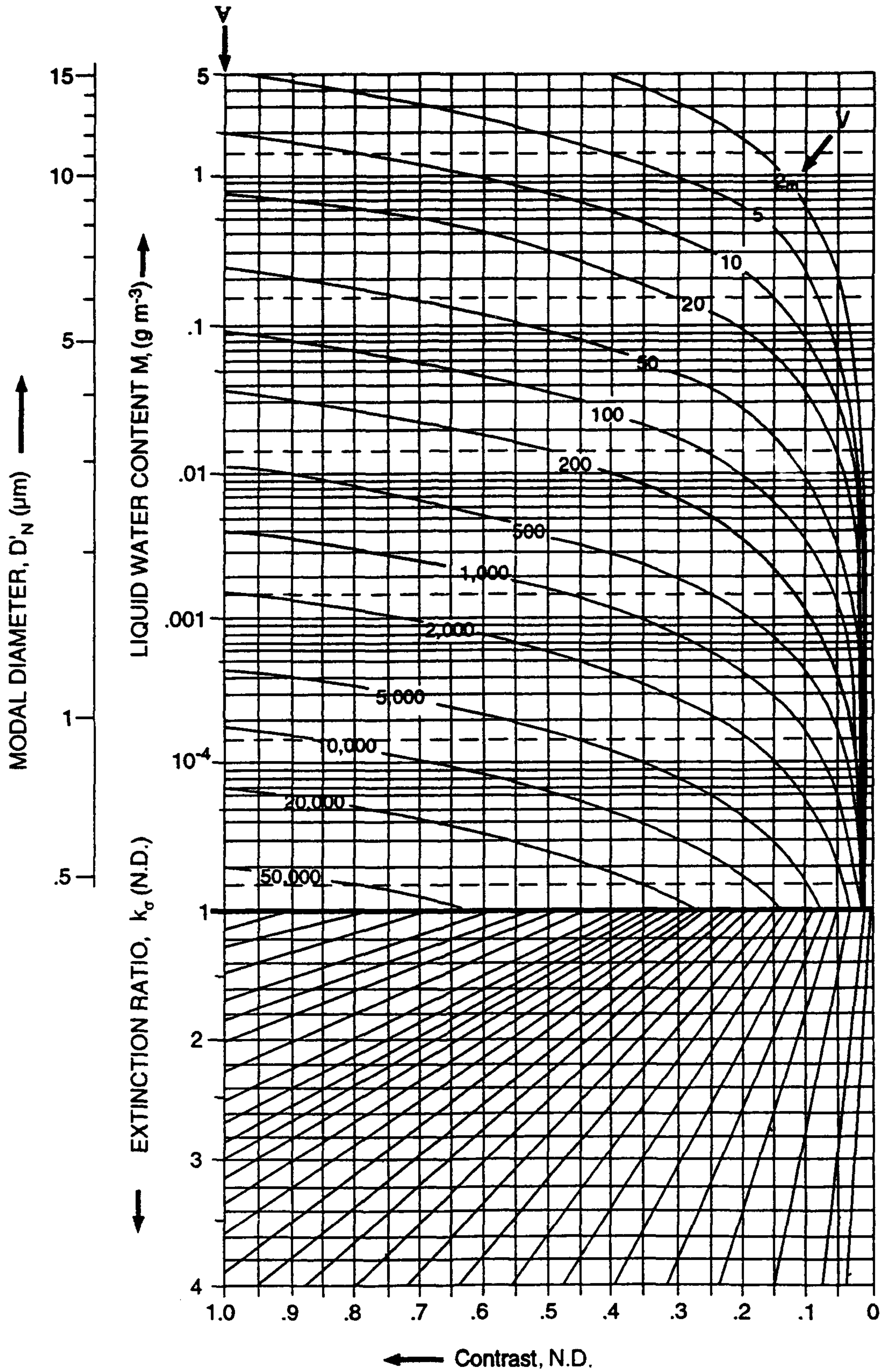

Figure 7. Nomogram for recognition visibility with isolines in meters ($D'_N = .01\ M^{.27}$ mm)

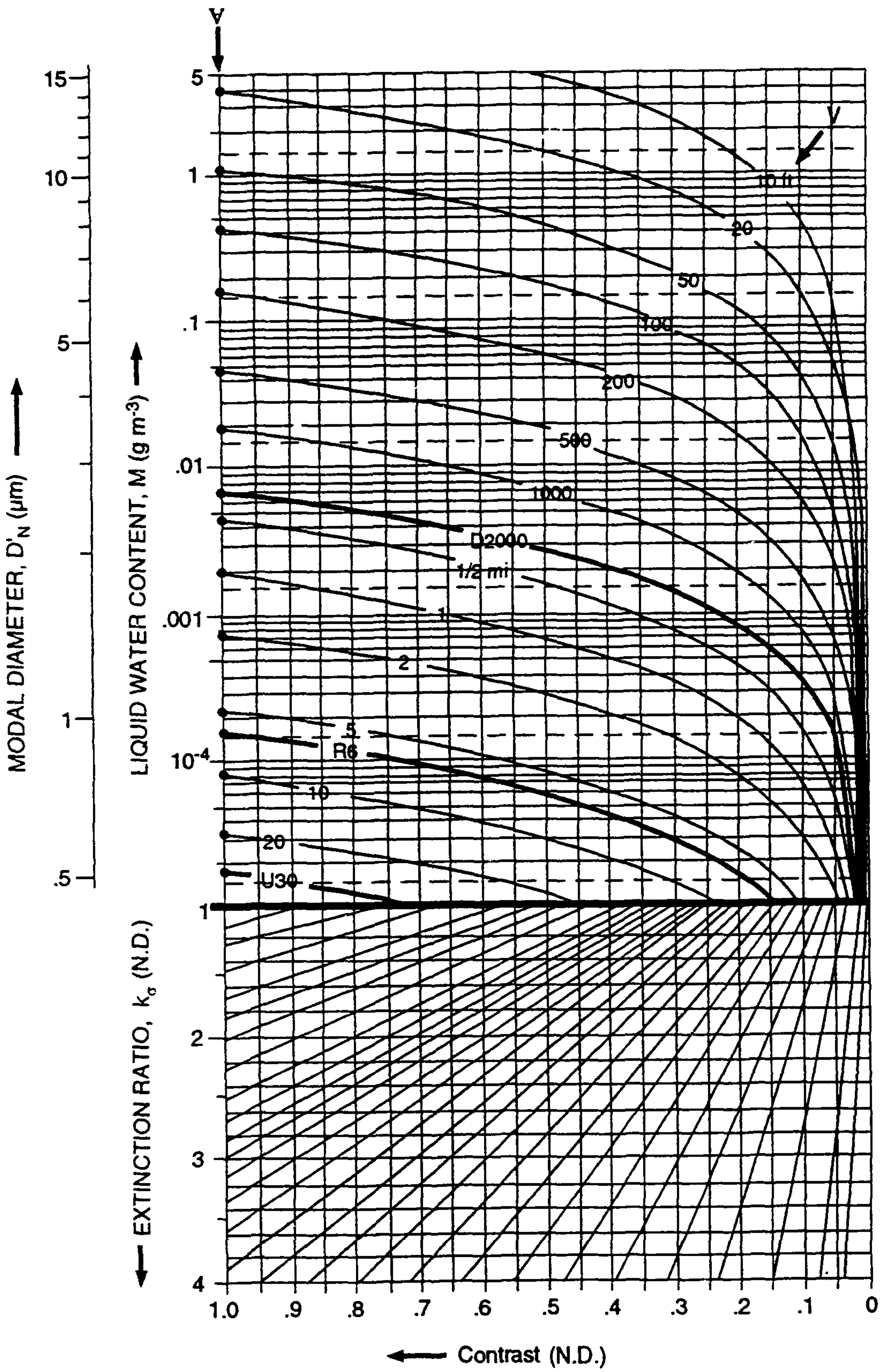

Figure 8. Nomogram for recognition visibility with isolines in miles and feet ($D'_N = .01\ M^{0.27}$ mm)

$$\forall_D = \frac{65.3\ M^{-0.73}\ r_M}{r_A} \quad m\ , \tag{78}$$

from Eq. (76).

The nomogram of Figure 9 illustrates the discernment ranges to be anticipated under the viewing conditions of Eqs. (77) and (78). The nomogram is similar to that of Figure 7, except that the isolines are now in terms of discernment visibility, V_D (in meters). The values of maximum discernment, $\forall_D$, are indicated along the vertical M scale at the places where the isolines intersect the M scale.

For applications, the nomogram of Figure 10 is provided, which is identical to Figure 9, except that the isolines of V_D have been drafted in feet and miles, analogous, and comparable to, the isolines of Figure 8.

The discussion of the significance of these nomograms will be limited to a comparison of Figures 8 and 10. Such comparison will more closely relate to, and provide examples of, our common, everyday seeing experiences, than will the other nomograms.

First of all, let us consider a synoptic weather observer who is required, on a given day, to report or not report the mandatory "visibility restriction" of 6 miles. In his report, does he subjectively "think" in terms of discernment or recognition? There is a possible factor of 2 ($\sim 1/2$ of 3.91) uncertainty involved in his report based on his personal way of thinking, as demonstrated by Figures 8 and 10. This is an intolerably-large uncertainty that can be immediately reduced by defining new standards of operational requirements.

Next, let us consider an aircraft pilot on final IFR approach to a Category II airport. Does he make his decision based on his first, vague view of the runway touchdown block (with its white stripes) or on his full and complete "recognition" of the block, stripes and runway? The answer probably lies "somewhere between." But it indicates how the pilot uses both of his visual skills (of discernment, first, followed by recognition); combined with his personal safety standards, to effect a satisfactory landing. This, too, is demonstrated, comparing Figures 8 and 10.

Finally, although numerous other examples of common experience could be cited, let us consider the viewing problem of a deer hunter on a somewhat foggy morning. His problem, if he is reckless, is to discern, as he walks through the woods, whether the living object ahead is a deer, as opposed to a farmer's cow, a bear, a moose, or another human being. Such reckless hunters exist and "shoot" on discernment. On the other hand, a cautious, legally-concerned, deer hunter will move/creep forward, until he can definitely recognize that he is stalking a deer and that the deer is a buck (legal) as opposed to a doe (illegal). The nomograms of Figures 8 and 10 indicate that if the visual situation of the morning is governed by a LWC of 0.01 g m^{-3}, a contrast condition of $\ln(1/\epsilon) = 0.2$ (contrast in the forest setting is "rather poor") and an extinction ratio of $k_\sigma = 1.5$, the cautious deer hunter will first discern the deer at a range of about 800 feet and will then have to move some 600 feet forward to his recognition that it is a legal buck.

The author trusts that he has made his point, about the reality of the two distinct types of viewing that humans, and all other living things with eyes, commonly experience daily and use routinely without any questions of definition or quantitative expression of definition. He also hopes that citing the examples versus the nomograms has provided instruction about the significance of the nomograms.

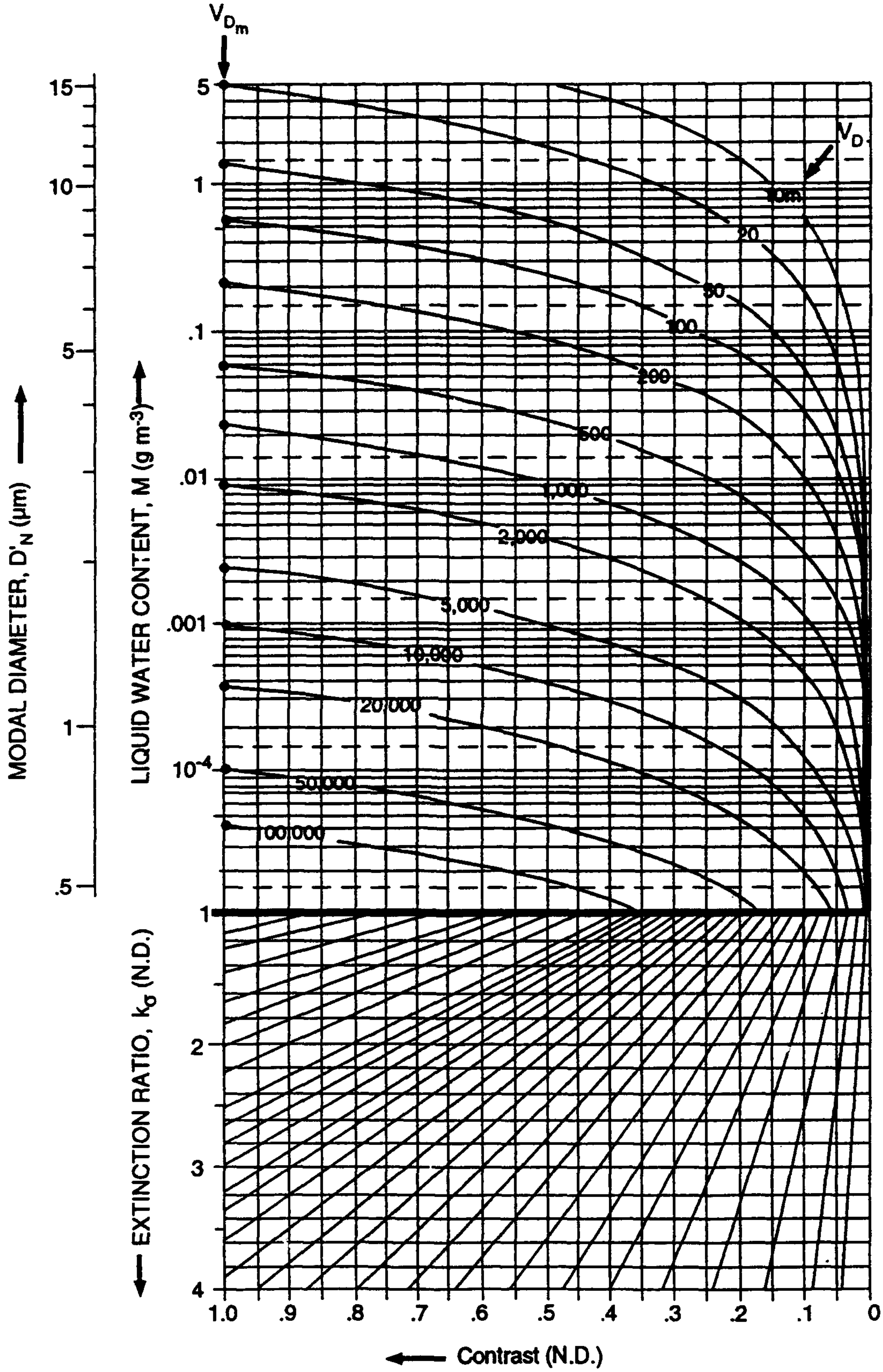

Figure 9. Nomogram for discernment visibility with isolines in meters ($D'_N = .01\ M^{0.27}$ mm)

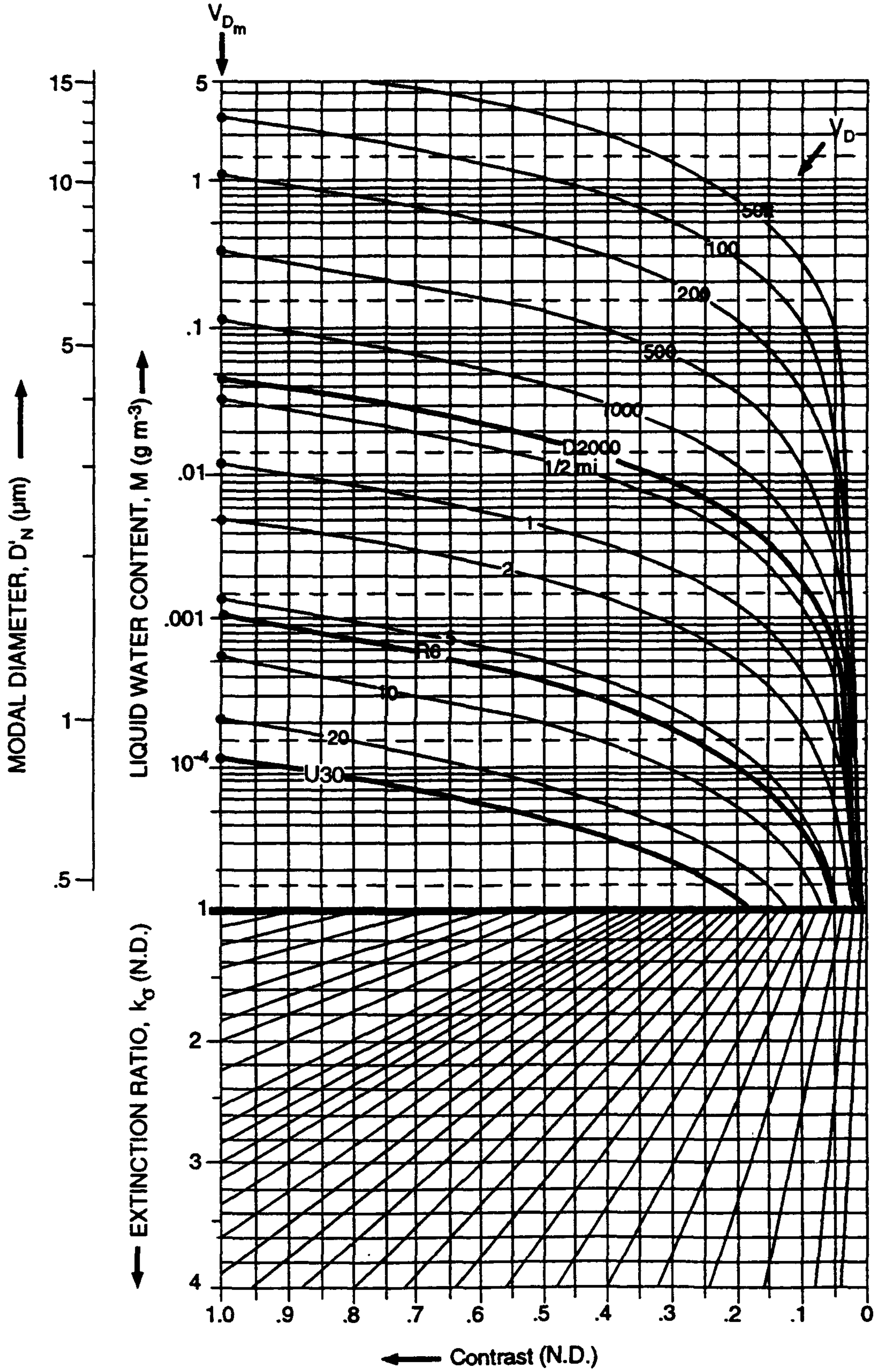

Figure 10. Nomogram for discernment visibility with isolines in miles and feet ($D'_N = .01\ M^{0.27}$ mm)

9.2 Comparisons with Other Visibility Studies

Visibility concepts and equations were historically developed over the years approximately as described below. The author uses the word "approximately" because, in his reading of the literature, he found that the record was not always "clear."

Trabert, in 1901, was probably the first to present the visibility equation

$$V = \frac{Cr}{M} \quad m\,, \tag{79}$$

where C is a particular constant, M is the liquid water content of the cloud droplets and r is the radius of the droplets (in μm).* The radius, r, is a variable, but Trabert failed to specify its exact definition. We now know, in hindsight, that the definition depends on the nature of the size distribution of cloud droplets and on the statistical procedures that might be used to obtain some measure of an "average."

Following Trabert, there was much discussion in the literature about the value of C in his visibility equation. For example, Conrad[38] (1901), also Wagner[39] (1909), determined the value to be 2.9. Richardson[40] (1919) found a value of 5.8 and Kohler[41] (1927) obtained a value of 3.05. Kohler[42] (1929) presented a revised value of 6.1, questioned the invariability of the constant and stated "that C in reality should be a function of cloud density." Stratton and Houghton[43] (1931), from the work of Mie[18] (1908), Debye[44] (1909) and Koschmieder[29, 30] (1924a, 1924b) found that the value should be 2.6, smaller than previously suspected.

The main channels of developmental thought leading to enhanced understanding of visibility flowed largely from the work of Koschmieder, and of Stratton and Houghton.

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* It may be that the historical record of visibility theory predates Trabert and that he merely extended the prior work of Helmholtz[32] (1896), Rayleigh[45] (1899) and/or others.

[38] Conrad, V. (1901) Über den Wassergehalt der Wolken (Water content of clouds). Denkschrift Math.-Naturwiss. *K. Akad. d. Wiss.*, **73**:115–131.

[39] Wagner, A. (1909) Untersuchungen der Wolkenelemente auf dem hohen Sonnblick. *Meteor. Z.*, **26**:371.

[40] Richardson, L.F. (1919) Measurements of water in clouds. *Proc. Roy. Soc. London, A*, **96**:19–31.

[41] Köhler, H. (1927) Zur kondensation des wasserdampfes in der atmosphäre (On water in the clouds). *Geophys. Publ.*, **5**. Oslo, 16 pp.

[42] Köhler, H. (1929) Wolkenuntersuchungen auf dem Sonnblick in Herbst 1928. *Meteor. Z.*, **46**:409–410.

[43] Stratton, J.A., and Houghton, H.G. (1931) A theoretical investigation of the transmission of light through fog. *Phys. Rev.*, **38**:159–165.

[18] Mie, G. (1908) Beiträge zur optik trüber medien, speziell kolloidaler metallosungen. *Ann. Phys.*, **25**:377–445 (Leipzig).

[44] Debye, P. (1909) Der lichtdruck auf kugeln von beliebigem material. *Ann. Physik*, **30**:57–136.

[29] Koschmieder, H. (1924) Theorie der horizontalen sichtweite. *Beiträge zur physik der freien atmosphäre*, **XII**:33–53.

[30] Koschmieder, H. (1924b) Theorie der horizontalen sichtweite II: kontrast und sichtweite. *Beitrage zur physik der freien atmosphare*, **XII**:171–181.

[32] Helmholtz, H.L.F. von (1896) *Handbuch der Physiologischen Optik*. Hamburg und Leipzig.

[45] Strutt, John W. (Lord Rayleigh) (1899) On the transmission of light through an atmosphere containing small particles in suspension, and on the origin of the blue of the sky. *Phil. Mag.*, **47**:375–384. Also, (1903) Sci Papers IV, 397.

Koschmieder did not deal directly with visibility, per se. Rather, he considered the effects of contrast *on visibility*. He found that the effects were governed by ln $(1/\epsilon)$, where ϵ is an "extinction quantity." He also established that optimum contrast—best seeing conditions—would occur for a perfect black-body-absorber contrasted against a perfectly white background. He then determined, from theoretical work, self-conducted experiments and reference to the findings of Helmholtz (loc. cit.), that ϵ, at the "threshold of contrast," when black and white blend together and can no longer be distinguished, has the value $\epsilon_0 = 0.02$, or $\ln (1/\epsilon_0) = 3.91$.

Koschmieder thus provided the equation

$$V_r = \frac{\ln (1/\epsilon)}{\sigma} \quad m, \tag{80}$$

where σ is the back-scattering cross-section of the cloud droplets.

For Koschmieder's threshold of contrast value of $\epsilon = \epsilon_0 = 0.02$, this becomes

$$V_r = \frac{3.91}{\sigma} \quad m. \tag{81}$$

Koschmieder was apparently unaware of the visibility equation of Trabert. There is no reference to Trabert in either of his papers.

Because of the lasting influence of the contributions of Stratton and Houghton to visibility theory, their assumptions and work leading to the development of their form of Trabert's equation are described and discussed in Appendix C.

In essence, (summarizing Appendix C) Stratton and Houghton (SH subsequently) assumed (1) a monodispersed distribution of cloud droplets all of common size. From the work of Mie[18] (1908) and Debye[44] (1909), they assumed (2) that the extinction ratio, k_{tr}, of previous reference, had the value 2.0. From Koschmieder's work, they assumed (3) that visibility could best be described by the Koschmieder "threshold of contrast" value of $\epsilon_0 = 0.02$ (which we now know is the "threshold of extinction" for discernment viewing).

From these three assumptions, SH determined that Trabert's equation should be written as

$$V = \frac{2.6\ r}{M} \quad m, \tag{82}$$

where r is the droplet radius for any given monodispersed population.

Unknowingly (hindsight is a good teacher), SH, by their assumption that contrast in visibility could best be handled by the simple specification of a constant threshold of contrast, eliminated the possibility of investigating the effects of variable contrast in the manner described by Koschmieder.

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[18] Mie, G. (1908) Beiträge zur optik trüber medien, speziell kolloidaler metallosungen. *Ann. Phys.*, **25**:377–445 (Leipzig).

[44] Debye, P. (1909) Der lichtdruck auf kugeln von beliebigem material. *Ann. Physik*, **30**:57–136.

There were numerous followers of SH, all of whom used the third SH assumption of constant contrast threshold. Most also used the second assumption. Few questioned the validity of the assumptions.

Investigative attention after SH thus focused primarily on the first SH assumption and on how droplet size distributions differing from monodispersed might effect the Trabert constant.

Aufm Kampe[46, 47] (1950a, b) examined his aircraft-acquired visibility data and the data of Diem[48] (1942) and concluded that the SH visibility equation was essentially correct, without change.

Aufm Kampe and Weickmann[49] (1952), after consideration of available information, concluded that the Richardson[40] (1919) form of Trabert's equation, that is,

$$V = \frac{5.8\,\bar{r}}{M} \quad m, \tag{83}$$

which had been used previously to determine LWC from measurements of visibility and droplet radius, was unsuitable for such application. They noted that, since the Trabert "constant" tends to increase as the droplet size spectra "broaden," the Stratton-Houghton Eq. (82), as modified to

$$V = \frac{2.6\,\bar{r}}{M} \quad m, \tag{84}$$

where $\bar{r}$ is a mean radius, might be used, with caution, for "narrow" spectra. But, with spectrum broadening, the constant would tend to increase from 2.6 toward Richardson's 5.8. Such a spectral broadening effect is verified in Appendix C, where the effect is discussed specifically.

Middleton[50] (1952), among other things, questioned the threshold of contrast value of Koschmieder. He emphasized that disagreements about this threshold were inevitable and pointed out that Houghton[51] (1939), from his investigations in fog, had deduced that $\epsilon_0 = 0.06$. Shallenberger and Little[52] (1940) experimentally determined a value of 0.032. Bricard[53] (1939)

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[46] Aufm Kampe, H.J. (1950) Visibility and liquid water content in clouds in the free atmosphere. *J. Meteorol.*, **7**:54-57.

[47] Aufm Kampe, H.J. (1950) Visibility and liquid water content in clouds in the free atmosphere. *J. Meteorol.*, **7**:166.

[48] Diem, M. (1942) Messungen der grosse von wolkenelementen I (Measuring the size of cloud elements). *Ann. der Hydrogr.*, Bd. 70.

[49] Aufm Kampe, H.J., and Weickmann, H.K. (1952) Trabert's formula and the determination of the water content in clouds. *J. Meteorol.*, **9**:167-171.

[40] Richardson, L.F. (1919) Measurements of water in clouds. *Proc. Roy. Soc. London, A*, **96**:19-31.

[50] Middleton, W.E.K. (1952) *Vision Through the Atmosphere*. Univ. of Toronto Press, Toronto, 105 pp.

[51] Houghton, H.G. (1939) On the relation between visibility and the constitution of clouds and fog. *J. Aer. Sci.*, **6**:408-411.

[52] Shallenberger, G.D., and Little, E.M. (1940) Visibility through haze and smoke and a visibility meter. *J. Opt. Soc. Amer.*, **30**:168-176.

[53] Bricard, J. (1939) Etude de la constitution des nuages au sommet du Puy-de-Dome. *Metorologie*, **20**, III-IV, 83-92.

obtained values from 0.0077 to 0.025. Douglas and Young[54] (1945), from measurements with a photoelectric telephotometer, found 0.055. Blackwell[55] (1949), investigating the calibration of his "disappearance range gauge," reported that ϵ_0 had to exceed 0.02.

Middleton, during the 1950–1951 period, conducted his own experiments to determine ϵ_0. Using a baffled photoelectric telephotometer, he stationed 10 observer airmen (at various ranges, presumably) to report the contrast between a "mark" and the sky background. Supposedly, a scale of contrast had been devised. This "mark contrast information," combined with that of the telephotometer, provided values of ϵ_0. Middleton found, from 1000 observations, as he stated, "an enormous range of ϵ_0 values." The median value was 0.031 and the data revealed variation from 0.005 to 0.155. Middleton also analyzed 285 observations acquired by Howell (unpublished) at Mount Washington and obtained similar results.

Such variability, however, *does not invalidate* the Koschmieder value of $\epsilon = 0.02$ for a perfect black body absorber contrasted against a perfectly white background. It merely means that the contrast "marks" and background references used by Middleton were less than perfect, in varying degree, and for those ϵ values he deduced to be smaller than 0.02 (implying a "better than perfect" contrast situation), there were possible errors of observation, measurement, analytical assumption, or computation.

Atlas and Bartnoff[56] (1953) verified and extended the Aufm Kampe/Weickmann work on spectral broadening. They domonstrated that the Trabert constant "had preferred values in natural clouds ranging from 3.3 for fair weather cumulus to 4.8 for nimbostratus." They found that visibility could be described better by the equation

$$V = \frac{K \rho D_0}{M} \quad m , \tag{85}$$

in which D_0 is the median volume diameter of the LWC distribution, ρ is the density of liquid water and K is a coefficient that is nearly independent of the breadth of the cloud droplet spectra. They worked with the distribution histograms of the multicylinder method [used by Clark[57] (1946) and Houghton[58] (1951)], to develop their equations. In particular, they found that $K = 1.2$ was in good correspondence with the 65 data observations of Diem[59] (1948) over the range of spectral breadths that occur in natural clouds.

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[54] Douglas, C.A., and Young, L.L. (1945) *Development of a Transmissometer for Determining Visual Range*. U.S. Dept. of Commerce, C.A.A. Tech. Div. Rep. No. 47.

[55] Blackwell, H.R. (1949) Report of progress of the Roscommon Visibility Tests, June 1947–Dec. 1948. Paper read to the Aviation Lighting Comm. of the I.E.S., Washington, Apr. 21, 1949.

[56] Atlas, D., and Bartnoff, S. (1953) Cloud visibility, radar reflectivity and drop-size distribution. *J. Meteorol.*, **10**:143–148.

[57] Clark, V.F. (1946) The multicylinder method. *Mt. Washington Mon. Res. Bull.*, **2**, No. 6.

[58] Houghton, H.G. (1951) On the physics of clouds and precipitation. *Compendium of Meteorology*. American Meteorological Society, Boston, 165–181.

[59] Diem, M. (1948) Messungen der grosse von wolkenelementen II (Measuring the size of cloud elements). *Met. Rund.*, Bd. 1, 261–273.

When K = 1.2 is substituted into Eq. (85), when ρ (= 10^6 g m^{-3}) is evaluated and when D_0 is expressed in μm, there results

$$V = \frac{1.2\ D_0}{M} \quad m\ , \tag{86}$$

which is the Atlas-Bartnoff form of Trabert's equation. Incidentally, the assumption of k_σ = 2.0 is incorporated in the equation, in accord with the second assumption of Stratton and Houghton.

Johnson[25] (1954), from scattering theory, demonstrated that

$$V_r = \frac{\ln(1/\epsilon)}{\sigma} \quad m\ , \tag{87}$$

is the *defining equation for visual range*. This is the same equation originally developed by Koschmieder (loc. cit.) which, for Koschmieder's threshold of contrast value of $\epsilon = \epsilon_0 = 0.02$, becomes Eq. (81).

Johnson, among the others, questioned the significance of the $\epsilon = 0.02$ threshold assumption and saw little justification for its use. He postulated that some other threshold value, rather than that for a black body, might better describe visual range in the real atmosphere. But he couldn't define an appropriate alternative.

Johnson also questioned the practice of virtually all authors reviewed herein of assigning k_σ, in their development of visibility equations, the value 2.0. From diffraction theory and Mie theory, he pointed out that k_σ would have the value 2 only under the condition $D/\lambda \leq 10$, where D is the droplet diameter and λ is the wavelength of the incident light. However, for $D/\lambda \geq 20$, k_σ would be 1.0. Thus, k_σ should vary from 1 to 2 over the normal size range of cloud droplets.* To express this another way, the "diffractive fringes" around cloud droplets, which increase their apparent size, will be larger for small droplets than for large droplets.

Johnson failed to consider the solar diffractive effects that are commonly observed as corona/glory phenomena. These, in the author's opinion, might increase values of k_σ to as much as 4, or so, if an observer is looking in the solar direction, or to 2, or so, in the anti-solar direction.

Johnson did not present a visibility equation but his work is of inestimable value to the theory.

This is the final paper that will be summarized here. We turn now to the principal topic of this section, which is a comparison of the visibility equation of the present report with the visibility equations of the investigators just cited. The equation of Koschmieder [Eq. (80)] cannot be considered, since it is not a visibility equation in terms of M.** This leaves the equations of Richardson, of Stratton and Houghton, and of Atlas and Bartnoff. The Richardson equation is

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* The author agrees with the logic of these statements of Johnson but not the details. There seems to be an inadvertent factor of 10 discrepancy in his D/λ value. It should probably read $D/\lambda \leq 1$, which, reference Appendix B, Figure B1 and Table B1, would make "better sense." The "weightings" that Johnson placed on other components affecting k_σ, reference Eqs. (44) and (46), are also unknown factors.

** This is irrespective of the Johnson assertion that the equation is definitive. Koschmieder did not develop σ in terms of LWC and scattering ratio. Johnson did.

[25] Johnson, J.C. (1954) *Physical Meteorology*. New York Technical Press, MIT and Wiley, 393.

included because it represents a possible upper bound to spectral broadening and may be compared with the equation of Atlas and Bartnoff.

We must now establish "comparability" among the KM Eq. (75) and Eqs. (82), (83), and (85).

For a monodispersed distribution of cloud droplets, the modal diameter *is* the diameter. Thence, the droplet radius r is related to D'_N as

$$r = \frac{D'_N}{2} \ \mu m. \tag{88}$$

For distributions of narrow spectral breadth, close to monodispersed, r in the above equation may be replaced by $\bar{r}$, without sensible error.

For the KM distribution function, the modal diameter of the LWC, or M_D, distribution is given by $D'_M = 2.5\ D'_N$ [Eq. (17)] and D_0 is usually about 1.2 times larger than D'_M. Thus, for the KM distribution,

$$D_0 \cong 3\ D'_N \quad \mu m \ . \tag{89}$$

The droplet size distributions of the multicylinder method, referenced by Atlas and Bartnoff, resemble the KM distributions. Therefore, it is presumed that the relation of Eq. (89) applies to the Atlas-Bartnoff visibility equation as well. Departures from the true relations should be relatively minor.

Thus, establishing comparability of droplet size among the previous and present visibility equations is relatively easy. The difficult part is to convert the present equation into some degree of "best correspondence" concerning matters of the definition of maximum "visibility/visual range" limits, of extinction ratio and of the normal, to be anticipated, "average contrast" of objects viewed. Proceeding along these lines, and neglecting truncation, the present visibility equation, [Eq. (75)], may be rewritten for the limit of discernment seeing, $\epsilon_0 = 0.02$, as assumed by all the others, to obtain the equation [Eq. (77) without truncation]

$$V_D = \frac{65.3 \ln (1/\epsilon)}{k_{\sigma} M^{0.73}} \quad m \ , \tag{90}$$

in which $D'_N = 10\ \mu m$ at $M = 1\ g\ m^{-3}$ is "built into" the equation as its "upper tie point." The "M factor" is placed in the denominator for ease of comparison.

The above equation still contains the extinction term, k_{σ}, and the contrast term, $\ln (1/\epsilon)$, which do not appear in the visual range equations of the other authors. Consequently, to compare equations, we must assume something about the anticipated values of the factors.

Johnson (loc. cit.) argued that $1 \leq k_{\sigma} \leq 2$, so a rough first assumption of average might be $k_{\sigma} = 1.5$. This applies to looking in the "cross-solar" direction. For looking in the solar direction, an arbitrary assumption is made that $k_{\sigma} = 3.5$. (The value should be smaller in the anti-solar direction, perhaps about 2.0.)

The author feels that an average contrast value, for a variety of objects lying around a 360° azimuth sweep at a typical observing site, might be something like C = 0.8.

When these k_o and C values are inserted in Eq. (90),

$$V_D = \frac{34.8}{M^{0.73}} \quad m , \tag{91}$$

when looking in the cross-solar direction, and

$$V_D = \frac{14.9}{M^{0.73}} \quad m , \tag{92}$$

when looking closely toward the sun.

The comparable equations of the other authors, when the size conversions of Eqs. (88) and (89) are accomplished for a D_N' value of 10 μm, become

$$V_D = \frac{29.0}{M} \quad m , \tag{93}$$

for Richardson,

$$V_D = \frac{12.5}{M} \quad m , \tag{94}$$

for Stratton and Houghton, and

$$V_D = \frac{36.0}{M} \quad m , \tag{95}$$

for Atlas and Bartnoff.

It should be emphasized that, technically, all of the above equations, (91) through (95), are equations that describe discernment rather than recognition visibility.

The predictions of these equations are compared in Table 1, for M values ranging from 10^{-5} to 5 g m^3. The visibility thresholds defined as unlimited, restricted, and "pilots' decision range" are indicated to the immediate right of the visual range tabulations by the horizontal black "bars" identified as "U," "R" and "D." The vertical location of the "bars," relative to the tabulations, has been "semi-interpolated" between values to provide a more accurate representation of the true locations of the threshold levels within the table. The common "tie point" for all equations being compared, of M = 1.0 g m^{-3}, is noted by the horizontal strip of screening.

The table reveals that, in general, and irrespective of the exact methods of equation determination by the different persons, there is a reasonable degree of harmony among predictions. The predictions do not differ wildly, by orders of magnitude. Rather, they differ mostly by factors of 1.2–4 throughout the comparable parts of the table (neglecting present concern with solar effects). The prior equations undoubtedly served the operational needs of weather-station

Table 1. A comparison of the visibility Eqs. (91) and (92) for discernment viewing with those of Richardson (1919), Stratton and Houghton (1931) and Atlas and Bartnoff (1953), for cloud LWCs ranging from 10^{-5} to 5 g m^{-3}, reference text.

Liquid Water Content	KM Distribution, as pertains to Discernment Visibility Looking		Richardson (1919) Equation	Stratton-Houghton (1931) Equation	Atlas-Bartnoff (1953) Equation
	Cross sun	Solar direction**			
	V =	V =	V =	V =	V =
g m^{-3}	m	m	m	m	m
5	10.7	4.60	5.80	2.50	7.20
2	21.0	8.98	14.5	6.25	18.0
1	34.8	14.9	29.0	12.5	36.0
.5	57.7	24.7	58.0	25.0	72.0
.2	113	48.2	145	62.5	180
.1	187	80.0	290	125	360
.05	310	133	580 —D	250	720 —D
.02	605 —D*	259	1450	625 —D	1800
.01	1000	430	2900	1250	3600
.005	1660	713 —D	5800	2500	7200
.002	3250	1390	14,500 —R	6250	18,000 —R
.001	5390	2310	29,000	12,500 —R	36,000
5×10^{-4}	8940	3830	58,000 —U	25,000	72,000 —U
2×10^{-4}	17,500 —R*	7470		62,500 —U	
1×10^{-4}	28,900	6660			
5×10^{-5}	48,000 —U*	20,600 —R			
2×10^{-5}	93,700	40,100			
1×10^{-5}		66,600 —U			

* "D" signifies a pilot's decision range, "R" indicates the visibility boundary of restricted/unrestricted and "U" symbolizes unlimited visibility.

** For looking in the *anti-solar* direction, multiply these listed visibilities by 2.

prediction rather well, with appropriate compensation by the individual stations for theory versus reality.

The table shows that the Stratton-Houghton equation is in general best accord with the Eq. (91) predictions herein.

There is another way of comparing the work herein with that of previous findings. Considerable effort was expended in the past to establish the characteristic droplet sizes and "visibilities" of natural, or internationally-defined, cloud types. This information is available for comparison and, in fact, can be exploited for immediate application.

The typical, average droplet radii of the internationally-defined, water-clouds identified in Table 2, as reported by Bricard (1940)[60], Diem (1942, 1948)[48, 59], Borovikov (1949)[61], Aufm Kampe (1950)[46], Lewis (1951)[62], Atlas and Bartnoff (1953*)[56] and Khrgian and Mazin (1963)[13], are listed in the data columns of the table. The average droplet radius, by cloud type, for all investigators, is shown in the last column of the table. (The fact that any single investigator did not report all types was ignored in the averaging, hence the table is admittedly biased toward those who did.)

The averages of the table reveal a distinct upward trend of droplet radii from the smaller/thinner natural clouds, that we intuitively suspect to have small liquid water content, toward the larger/thicker clouds, in which we anticipate large LWC.

In Table 3, the data of Table 2 have been converted from mean radii, $\bar{r}$, into modal diameter, using the equation

$$D_N' = 4/3\,\bar{r} \qquad \mu m\,, \tag{96}$$

which, although applying strictly to the KM distribution function, is also presumed to apply approximately to the multifarious data distributions and/or distribution functions used by the other investigators.

From the D_N' averages of Table 3, the corresponding values of LWC for the different cloud types were computed from Eq. (59) reversed. The values are listed in the last column of Table 3.** From these LWC values, we may proceed to a comparison of available measurement data with available equations.

Aufm Kampe (loc. cit.) provided aircraft-measured values of visual-range obtained from flight through the several types of internationally-defined, water clouds indicated in Table 4. To obtain his range measurements, Aufm Kampe used a light with a parallel beam that was mounted on one wing tip of his reasearch aircraft. A receiver, consisting of a selenium photronic cell, was

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* The Atlas-Bartnoff (AB) listings of $\bar{r}$ in Table 2 represent a "special case," in that AB provided their own equation for $\bar{r}$ for the different types of natural clouds. Their equation and tabulations have been used in Table 2 and the author has been very careful not to violate their work.

** A question might be asked as to why these LWC values were inferred from droplet size measurements rather than obtained from direct LWC measurements. Rarely did previous investigators report LWC values by cloud type, and, when they did, as, for example, Borovikov, et al., (1963)[61] and Lewis (1947, 1951)[35,62] the values were presented as ranges by altitude within the clouds, as values versus cloud temperature, as ranges of occurrence frequency, etc. The droplet size data, on the other hand, are more plentiful, specific and trustworthy.

[61] Borovikov, A.M. (1949) Nekotorye rezul'taty izucheniya oblachnykh elementov (Some results of a study of cloud elements). *Trudy Tsentral Aerolog. Obsv.*, No. 3.

[62] Lewis, W. (1951) Meteorlogical aspects of aircraft icing. Compendium of Meteorology, Amer. Meteor. Soc., Boston, 1197-1203.

Table 2. Average droplet radii for natural cloud types as reported by different investigators.

Cloud Type	Bricard[60] (1940) $\bar{r}$ μm	Diem[48,59] (1942, 1948) $\bar{r}$ μm	Borovikov[61] (1949) $\bar{r}$ μm	Aufm Kampe[46,47] (1950) Typical Average $\bar{r}$ μm	Lewis[62] (1951) over U.S.A. $\bar{r}$ μm	Atlas-Bartnoff[56] (1953) Reference Text $\bar{r}$ μm	Khrgian-Mazin[13] (1963) $\bar{r}$ μm	Average by Type $\bar{r}$ μm
Cumuliform								
Fair weather								
cumulus......Cu				4.0	7.8	6.8	4	5.6
Stratocumulus.Sc	7.6	5.4	8.2	3.5	5.4	7.0	5	6.0
Alto cumulus..Ac			7.1		7.1	7.5	6	6.9
Cumulus								
congestus.....Cg					7.8	6.3	9	7.7
Stratiform								
Stratus..........St	4.2	6.0	4.6	6.5	5.4	6.9	6	5.7
Alto stratus...As				5.6	7.1	7.5	5	6.3
Translucidus.."								
Opacus........."						7.5		
Nimbostratus..Ns	9.8	6.0	12.0			6.1	8	8.4

[60] Bricard, J. (1940) Nature des nuages en relation avec les dimensionss des particules qui les constituent. *C.R. Acad. Sci.* Paris. **210**, 148–150.

[48] Diem, M. (1942) Messungen der grosse von wolkenelementen I (Measuring the size of cloud elements). *Ann. der Hydrogr.*, Bd. 70.

[59] Diem, M. (1948) Messungen der grosse von wolkenelementen II (Measuring the size of cloud elements). *Met. Rund.*, Bd. 1, 261–273.

[61] Borovikov, A.M. (1949) Nekotorye rezul'taty izucheniya oblachnykh elementov (Some results of a study of cloud elements). *Trudy Tsentral Aerolog. Obsv.*, No. 3.

[46] Aufm Kampe, H.J. (1950) Visibility and liquid water content in clouds in the free atmosphere. *J. Meteorol.*, **7**:54–57.

[47] Aufm Kampe, H.J. (1950) Visibility and liquid water content in clouds in the free atmosphere. *J. Meteorol.*, **7**:166.

[62] Lewis, W. (1951) Meteorlogical aspects of aircraft icing. Compendium of Meteorology, Amer. Meteor. Soc., Boston, 1197–1203.

[56] Atlas, D., and Bartnoff, S. (1953) Cloud visibility, radar reflectivity and drop-size distribution. *J. Meteorol.*, **10**:143–148.

[13] Khrgian, A.Kh., and Mazin, I.P. (1963) *Cloud Physics*. Israel Prog. Sci. Transl., Jerusalem, 392 pp.

Table 3. Typical modal diameters for natural cloud types as converted from the original data.

Cloud Type	Bricard[60] (1940) D'_N μm	Diem[48,59] (1942, 1948) D'_N μm	Borovikov[61] (1949) D'_N μm	Aufm Kampe[46,47] (1950) Typical Average D'_N μm	Lewis[62] (1951) over U.S.A. D'_N μm	Atlas-Bartnoff[56] (1953) Reference Text D'_N μm	Khrgian-Mazin[13] (1963) D'_N μm	Average by Type $\overline{D'_N}$ μm	Corresponding KM LWC $\overline{M}$ g m^{-3}
Cumuliform									
Fair weather									
cumulus......Cu				5.3	10.4	9.0	5.3	7.5	.346
Stratocumulus.Sc	10.1	7.2	11.0	4.7	7.2	9.4	6.7	8.0	.439
Alto cumulus..Ac			9.5		9.5	10.0	8.0	9.2	.736
Cumulus									
congestus.....Cg					10.4	8.4	12.0	10.3	1.12
Stratiform									
Stratus..........St	5.6	8.0	6.1	8.7	7.2	9.2	8.0	7.6	.363
Alto stratus...As				7.5	9.5	10.0	6.7	8.4	.526
Translucidus.."									
Opacus........."								10.0	1.00
Nimbostratus..Ns	13.1	8.0	16.0			8.1	10.7	11.2	1.52

[60] Bricard, J. (1940) Nature des nuages en relation avec les dimensionss des particules qui les constituent. *C.R. Acad. Sci.* Paris. **210**, 148–150.

[48] Diem, M. (1942) Messungen der grosse von wolkenelementen I (Measuring the size of cloud elements). *Ann. der Hydrogr.*, Bd. 70.

[59] Diem, M. (1948) Messungen der grosse von wolkenelementen II (Measuring the size of cloud elements). *Met. Rund.*, Bd. 1, 261-273.

[61] Borovikov, A.M. (1949) Nekotorye rezul'taty izucheniya oblachnykh elementov (Some results of a study of cloud elements). *Trudy Tsentral Aerolog. Obsv.*, No. 3.

[46] Aufm Kampe, H.J. (1950) Visibility and liquid water content in clouds in the free atmosphere. *J. Meteorol.*, **7**:54–57.

[47] Aufm Kampe, H.J. (1950) Visibility and liquid water content in clouds in the free atmosphere. *J. Meteorol.*, **7**:166.

[62] Lewis, W. (1951) Meteorlogical aspects of aircraft icing. Compendium of Meteorology. Amer. Meteor. Soc., Boston, 1197-1203.

[56] Atlas, D., and Bartnoff, S. (1953) Cloud visibility, radar reflectivity and drop-size distribution. *J. Meteorol.*, **10**:143–148.

[13] Khrgian, A.Kh., and Mazin, I.P. (1963) *Cloud Physics*. Israel Prog. Sci. Transl., Jerusalem, 392 pp.

Table 4. Comparisons of visual ranges among the predictions of Atlas and Bartnoff (1953), of Equations 91 and 92, herein, and of the measurements of Aufm Kampe (1950)

Cloud Type	Average LWC	Visual Range: From Equations (91) and (92) herein	Visual Range: Aufm Kampe Aircraft Measurements	Visual Range: Atlas and Bartnoff Reference Text		
	M $g\ m^{-3}$	V_r m	V_r m	D_0 μm	K(n) N.D.	V_r m
Cumuliform						
Fair weather cumulus..Cu	0.346	19–76	40	15.4	1.32	59
Stratocumulus.............Sc	0.439	16–64	100	15.9	1.91	69
Altocumulus.................Ac	0.736	11–44		17.0	1.64	39
Cumulus congestus......Cg	1.12	8–32	20	14.3	1.68	21
Stratiform						
Stratus...........................St	0.363	19–73	140	15.7	1.39	60
Alto stratus....................As	0.526	14–56	150	17.0	1.64	53
Translucidus.............As						
Opacus......................As	1.00	9–35		17.0	1.64	29
Nimbostratus................Ns	1.52	6–26		13.8	1.72	16

mounted on the other wing tip. The distance between transmitting beam and receiver was 16 m (52 feet). He used a moving coil galvanometer for a sensor and with computational reference to the work of Koschmieder (for discernment viewing conditions) he deduced the visual-range results shown in Table 4 (in the middle column under "visual range"). He noted that engine vibration caused appreciable uncertainty in his calculations. (Aufm Kampe failed to mention how he handled the problem of contrast between some sort of "black body reference" and the background.)

To compare with these measurements of Aufm Kampe, we seemingly have only the equation of Atlas and Bartnoff (loc. cit.) and the equations presented herein.

Atlas and Bartnoff developed the visual-range equation, Eq. (85) herein, that was "partially discussed" previously. Although they concluded that $K = 1.2$, in their equation, was the best value for "clouds of all types," they also provided a table of K(n), or K, values that was "type specific" and was computed in three different ways. The author has concluded that the column 2 values of their Table 5 are the most descriptive of internationally-defined clouds. Atlas and Bartnoff *did not* provide LWC information about natural cloud types, but, this is understandable since, as the author has noted, such information is extremely difficult to obtain, except by the indirect methods used relative to Table 3.

From Table 3, it is seen that the "upper tie point of LWC," for the visibility work herein, namely $M = 1.0\ g\ m^{-3}$, lies "somewhere within" the natural cloud type identified as nimbostratus

opaqus.* From this assumption, which is really not an assumption but a mere acceptance of data findings, the visual range predictions of the Atlas-Bartnoff equation [Eq. (85) herein, with K = K(n)] can be determined from the LWC, D_0, and K(n) values identified in Table 4. Their visual-range results for natural clouds are presented in the last column of the table.

The visual-range values of Eqs. (91) and (92) are shown in the first column of the table section thus identified. The first of the values is for the restrictive situation of looking in the solar direction [Eq. (92)]; the second is for the more usual situation of looking "cross sun" [Eq. (91)].

The table reveals fair agreement (to within about ± 27 percent), for cumuliform cloud types, between the visual range predictions of Atlas-Bartnoff (AB) and the measurements of Aufm Kampe (AK). For stratiform cloud types, however, the AB equation appreciably "underpredicts" the AK measurements (by about −80 percent).

The Eq. (91) values (neglecting the special case condition of looking toward the sun) are also in reasonable agreement with AK for cumuliform cloud types (to within about ± 50 percent) and agree with AB (within about ± 22 percent). But, for stratiform cloud types, although Eq. (91) overpredicts AB (by about + 23 percent), both Eq. (91) and that of AB appreciably underpredict AK (by about −70 to −80 percent).

The discussion will now turn to consideration of how information about visibility can be used to obtain values of other cloud physics quantities. A particular example has been selected, as explained in the following section.

9.3 Estimates of M from V—A Consideration of Uncertainties, Research Needs and Questions of Visibility Definitions

From the equation listings [Eqs. (60) through (74) in Sec. 8], it is seen that, in theory, it is possible to employ observations or measurements of visibility to deduce the line integral averages of the quantities, N, A, M, or Z, along the visibility paths from the observer to the object(s) seen. In this section, the particular relation, involving the estimation of M from V, has been selected as an example of the accuracies to be expected and of the relative contributions of the several uncertainty terms (indicating where research efforts are needed). As a serendipitious "spinoff," the example also reveals an aspect of visibility theory that has been neglected to date.

The reader who is not especially interested in the mathematical details of uncertainty analyses may skip to the discussion following Eq. (120), in which Table 5 is explained, and the results are discussed.

The visibility equation of the present report, Eq. (75), becomes, when solved for M,

$$M = 47.3 \left[\frac{\ln(1/\epsilon)\, r_M}{V\, k_\sigma\, r_A} \right]^{1.37} \qquad \text{g m}^{-3}\,. \tag{97}$$

If, for convenience, we define

$$T_V = V^{-1.37} \qquad \text{N.D.} \tag{98}$$

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* It also lies "somewhere within" the convective cloud type "cumulus congestus," but the author prefers to relate his reference to the homogeneous, time-stable, cloud-type "Ns opaqus," rather than to the non-homgeneous, time-variable type "Cg."

to be the visibility term,

$$T_C = [\ln(1/\epsilon)]^{1.37} \qquad \text{N.D.} \qquad (99)$$

to be the contrast term,

$$T_E = k_\sigma^{-1.37} \qquad \text{N.D.} \qquad (100)$$

to be the extinction term, and

$$T_T = \left(\frac{r_M}{r_A}\right)^{1.37} \qquad \text{N.D.} \qquad (101)$$

to be the truncation term, then Eq. (97) may be modified to

$$M = 47.3\, T_V\, T_C\, T_E\, T_T \qquad \text{g m}^{-3}\,, \qquad (102)$$

where all necessary conversion units are carried in the constant "47.3."

For uncertainty (error bound) estimation, Eq. (102) may be totally differentiated to obtain

$$dM = \frac{\partial M}{\partial T_V} dT_V + \frac{\partial M}{\partial T_C} dT_C + \frac{\partial M}{\partial T_E} dT_E + \frac{\partial M}{\partial T_T} dT_T \qquad \text{g m}^{-3}\,. \qquad (103)$$

This may also be written, in terms of decimal (percentage) uncertainty, as

$$\frac{dM}{\bar{M}} = \frac{\partial M}{\partial T_V}\frac{dT_V}{\bar{T}_V} + \frac{\partial M}{\partial T_C}\frac{dT_C}{\bar{T}_C} + \frac{\partial M}{\partial T_E}\frac{dT_E}{\bar{T}_E} + \frac{\partial M}{\partial T_T}\frac{dT_T}{\bar{T}_T} \qquad \text{N.D.}\,, \qquad (104)$$

where $\bar{M}$ is the average value of M from Eq. (102).

The right hand terms of the above equation are, respectively, from Eqs. (98)–(102).

$$\frac{\partial M}{\partial T_V}\frac{dT_V}{\bar{T}_V} = -1.37\, V^{-2.37} \qquad \text{N.D.}\,, \qquad (105)$$

$$\frac{\partial M}{\partial T_C}\frac{dT_C}{\bar{T}_C} = 1.37\, [\ln(1/\epsilon)]^{0.37} \qquad \text{N.D.}\,, \qquad (106)$$

$$\frac{\partial M}{\partial T_E}\frac{dT_E}{\bar{T}_E} = -1.37\, k_\sigma^{-2.37} \qquad \text{N.D.}\,, \qquad (107)$$

and

$$\frac{\partial M}{\partial T_T}\frac{dT_T}{\bar{T}_T} = 1.37\, (r_M/r_A)^{0.37} \qquad \text{N.D.}\,. \qquad (108)$$

Hence, Eq. (104), written in finite difference terms, becomes

$$\frac{\Delta M}{\bar{M}} = 1.37 \left\{ -V^{-2.37} \frac{\Delta T_V}{\bar{T}_V} + [\ln(1/\epsilon)]^{0.37} \frac{\Delta T_C}{\bar{T}_C} - k_{,,}^{-2.37} \frac{\Delta T_E}{\bar{T}_E} + \left(\frac{r_M}{r_A} \right)^{0.37} \frac{\Delta T_T}{\bar{T}_T} \right\} \quad g\ m^{-3} \ . \tag{109}$$

This is the uncertainty, or "error bounds," equation tha applies to the estimate of M values from observations or measurements of recognition visibility. Such estimates can also be obtained for discernment visibility but are not considered here.

The average, expected, values of contrast and extinction-ratio (not looking in the solar or anti-solar directions) were stated before in the report. Hence, when the contrast, $\ln(1/\epsilon) = 0.8$ and $k_{,,} = 1.5$ are introduced into Eq. (109),

$$\frac{\Delta M}{\bar{M}} = 1.37 \left[-V^{-2.37} \frac{\Delta T_V}{\bar{T}_V} + 0.92 \frac{\Delta T_C}{\bar{T}_C} - 0.38 \frac{\Delta T_E}{\bar{T}_E} + \left(\frac{r_M}{r_A} \right)^{.37} \frac{\Delta T_T}{\bar{T}_T} \right] \quad g\ m^{-3} . \tag{110}$$

The average values of $\ln(1/\epsilon)$ and $k_{,,}$ just cited result in values of $\bar{T}_C = 0.74$ and $\bar{T}_E = 0.57$, from Eqs. (99) and (100). This enables a further simplification of Eq. (110) to

$$\frac{\Delta M}{\bar{M}} = 1.37 \left[-V^{-2.37} \frac{\Delta T_V}{\bar{T}_V} + 1.27\ \Delta T_C - 0.67\ \Delta T_E + \left(\frac{r_M}{r_A} \right)^{0.37} \frac{\Delta T_T}{\bar{T}_T} \right] \quad N.D. \ . \tag{111}$$

We now consider the *important* uncertainty terms, ΔT_V, ΔT_C, ΔT_E, and ΔT_T, of this equation. From previous discussion and our present state of knowledge, these may be estimated as follows, where the estimations are described to the extent required for each.

The visibility uncertainties of Eq. (111) are range-visibility dependent. They are assumed to obey the approximate equation relationship,

$$\Delta V \cong \pm\ 0.2\ V \quad m \ . \tag{112}$$

This equation relates to our common visibility experience. It implies, for example, that a research person, working with a cloud chamber of 15 foot dimension, can detect visibility changes to within ± 4 feet. It implies that a weather observer, at an airport station, can differentiate between a visibility of 1/8 mile (660 feet) and 1/16 mile (330 feet). It means that an aircraft pilot, flying at his IFR decision range of 2000 feet, approaching an "obscured" airport to land, has nervous concerns about landing, because he knows, mentally, that the seeing situation has uncertainties of about ± 400 feet. It means that a synoptic-scale weather observer can only predict the defined boundary of "restricted visibility," 6 miles, to within ± 1.2 miles, or the semi-defined boundary of "unlimited visibility," 30 miles, to within ± 6 miles.

These visibility examples of uncertainty, with which the reader may or may not concur, should roughly describe everyday experiences in seeing, decision, and prediction.

In view of the above, and Eqs. (98) and (112), the uncertainty term, ΔT_V, of Eq. (111), becomes

$$\Delta T_V = -1.37\ V^{-2.37} \quad \Delta V = \pm\ .274\ V^{1.37} \quad m \ . \tag{113}$$

The other uncertainty terms of Eq. (112) do not share the property of being range-visibility dependent.

The uncertainties of contrast, ln $(1/\epsilon)$, can probably, with diligence, be estimated to about $\pm$ 0.2, such that ΔT_C, of Eq. (112), becomes

$$\Delta T_C \cong \pm\, 0.274\, [\ln (1/\epsilon)]^{0.37}\,, \tag{114}$$

working through Eq. (99).

The extinction ratio, k_σ, again assuming that viewing avoids the solar or anti-solar directions, should be estimable to $\pm$ 0.2 (or better, with a bit of theoretical effort). Hence,

$$\Delta T_E = \pm\, 0.274\, k_\sigma^{-2.37}\,, \tag{115}$$

from Eq. (100).

The truncation uncertainty ΔT_T really doesn't exist, if viewing is performed by human beings. Humans have sufficient "bandwidth(s)" in their seeing abilities to trivialize such problems. However, when *instruments* are used to measure visibility, truncation limits and uncertainties can be important. For the moment, it is assumed that

$$\Delta T_T = 0\,. \tag{116}$$

When these uncertainty values of Eqs. (113)-(116) are substituted in Eq. (111),

$$\frac{\Delta M}{\bar{M}} = 1.37 \left\{ \pm \frac{0.274\, V^{-3.74}}{\bar{T}_V} \pm 0.348\, [\ln (1/\epsilon)]^{0.37} \pm 0.184\, k_\sigma^{\,2.37} \right\} \quad \text{N.D.}\,, \tag{117}$$

or, from Eq. (98), and since $\ln (1/\epsilon) = \overline{\ln (1/\epsilon)} = 0.8$ and $k_\sigma = \overline{k}_\sigma = 1.5$,

$$\frac{\Delta M}{\bar{M}} = \pm\, 0.375\, V^{-2.37} \pm 0.439 \pm 0.0964 \qquad \text{N.D.}\,. \tag{118}$$

This is the decimal (percentage) uncertainty equation pertaining to the estimation of LWC from the visibility equation, Eq. (75), of the present report.

For the average values previously mentioned, and from Eqs. (98)-(100), $\bar{T}_V = \bar{V}^{-1.37}$, $\bar{T}_C = 0.737$, $\bar{T}_E = 0.574$ and $\bar{T}_T = 1.0$. When these values are introduced into Eq. (102), the average value of LWC is given by

$$\bar{M} = 20.0\, \bar{V}^{-1.37} \qquad \text{g m}^{-3}\,. \tag{119}$$

To be very specific, *$\bar{M}$ is the path integral average of liquid water content along the line of sight.* Equation (119) may be inserted into Eq. (118) to obtain

$$\Delta M = \pm\, 7.5\ \ \bar{V}^{-3.74} \pm 8.78\ \ \bar{V}^{-1.37} \pm 1.93\ \ \bar{V}^{-1.37} \qquad \text{g m}^{-3} \tag{120}$$

which is the equation for the absolute uncertainties of $\bar{M}$.

Values of $\bar{M}$ (center column), of the decimal uncertainties (left hand columns) and of the absolute uncertainties (right hand columns), as computed from Eqs. (118)-(120), are listed in Table 5. Four visibility situations are considered in the table and the situations are tabulated in the order of increasing range, or visibility. These are the same situations mentioned earlier, now being examined in detail relative to estimates of $\bar{M}$.

It is seen, first of all, from the total of the decimal uncertainties, that the $\bar{M}$ estimates from observed or measured visibility are about ±0.55 (± 55 percent) uncertain at all ranges. This capability can be exploited, now, from current observational/measurement techniques. The uncertainties might seem large to the reader but it must be emphasized that they are not factors of 2, or 5 (such as are common in radar meteorology) nor are they orders of magnitude, as might have been suspected prior to the current investigation. The $\bar{M}$ values are eminently useful even in view of the uncertainties.

The second thing the table demonstrates is that the contrast-component contributes about 80 percent to the total uncertainty. This tells us immediately that it is here where research effort ought to be concentrated to improve the $\bar{M}$ vs V estimates. Research work in diffraction theory can also reduce the uncertainties of the extinction term, as mentioned earlier. It would seem that such efforts, even minimum, could quickly reduce the $\bar{M}$ uncertainties from the present ± 55 percent to perhaps about ± 30 percent. No LWC instrument now in existence can even begin to approach these measurement accuracies, expecially for very small values of LWC.

It is difficult to understand the finding that the ΔV uncertainties of visibility assumed relative to Eq. (112) (which, "on the surface," would appear to be a reasonable assumption), should contribute so slightly, termwise, to the total uncertainties of Eqs. (118) and (120) as listed in Table 5. The explanation lies, of course, in the large negative exponent on V that appears in the first term of Eq. (117). But, the finding is "bothersome." It would seem that some aspect of visibility theory that is important to understanding may have been neglected.

This "aspect," in the authors' opinion, is a consideration of the visibility situation of a perfectly clear day devoid of any cloudy obstructions. How do we consciously or unconsciously define "visibility" on such day? The visibility equations developed herein do not tell us, yet this is a very important "limiting case" that may enhance our knowledge.

The matter is explored in the following section.

9.4 Discernment and Recognition Ranges, Corresponding Visibility Equations and Summary of Visibility Findings

There are four quantities that are obviously involved in the "recognition" of an object under clear-air conditions:

1. the size of the object viewed,
2. the range from which it is viewed,
3. the contrast of the object relative to its immediate surroundings,
4. the detailed features that exist on or are a part of the object (shape, protuberances, depressions, holes, marks, lettering, etc.) the viewing of which, at some subjective "level of detail" is regarded as "recognition."*

* There is a fifth quantity that is also involved here. This is a loss of resolution due to optical aberration (scintillation) caused by atmospheric turbulence, which is highly dependent on the time of day, location and line of sight. The effects act to reduce contrast; hence reduce visibility.

Table 5. Component and total uncertainties in the path integral averages of $\bar{M}$ when obtained from measurements of visibility. The decimal uncertainties are tabulated at the left; the absolute uncertainties are listed at the right.

Visibility Situation	Decimal Uncertainties				$\bar{M}$	Absolute Uncertainties			
	Visibility Term N.D. ±	Contrast Term N.D. ±	Extinction Term N.D. ±	Total ND ±	$g\ m^{-3}$	Visibility Term $g\ m^{-3}$ ±	Contrast Term $g\ m^{-3}$ ±	Extinction Term $g\ m^{-3}$ ±	Total $g\ m^{-3}$ ±
Research/Experiment *[Range 15 ft (4.6 m)]*	0.0101	0.439	0.0964	0.546	2.47	0.0249	1.09	0.239	1.35
Aviation Observer [Range 500 ft (150 m)]	2.61×10^{-6}	0.439	0.0964	0.535	0.0209	5.45×10^{-8}	0.00916	0.00202	0.0112
Pilot Landing Decision [Range 2000 ft (610 m)]	9.40×10^{-8}	0.439	0.0964	0.535	0.00306	3.83×10^{-11}	0.00134	2.95×10^{-4}	0.00164
Restricted Visibility [Range 6 mi (10,000 m)]	1.24×10^{-10}	0.439	0.0964	0.535	6.62×10^{-5}	8.22×10^{-15}	2.91×10^{-5}	6.39×10^{-6}	3.55×10^{-5}
Unlimited Visibility [Range 30 mi (48,000 m)]	3.02×10^{-12}	0.439	0.0964	0.535	7.72×10^{-6}	2.33×10^{-17}	3.39×10^{-6}	7.45×10^{-7}	4.14×10^{-6}

The equation that describes the "recognition range" is

$$R_R = C\, s\, f \ln (1/\epsilon) \qquad m\,, \tag{121}$$

where s is the object size, in meters, $\ln (1/\epsilon)$ is the contrast, [following Koschmieder (loc. cit.)] non-dimensional, f is the "feature ratio," non-dimensional, and C is a constant to be evaluated, also non-dimensional. The equation is logical in that R_R is anticipated to increase directly with increasing object size and contrast. The logic of the direct dependence of R_R on f will be explained.

Equation (121) is "object specific," which means that we must have selected the object, know its size and, most importantly, know its feature details, as parameterized by f, and its contrast, relative to background.

The feature ratio f is the ratio of feature size to object size. Thus,

$$f = \frac{s_f}{s} \qquad \text{N.D.}\,, \tag{122}$$

where s_f is the feature size (or an average or predominant size).

The value of f varies from its maximum value of 1.0, when feature size equals object size, to some small value that could even approach zero, such as in the case of visually examining the grain structure of a rock to identify its geological classification (without microscope). However, in common visibility experience, the actual f values should seldom be smaller than about 0.1 or so. This implies that the feature sizes required for recognition would be larger than one tenth the size of the object.

An f value, larger than 0.1 does exist, however, that would reflect a "level of detail" (or f value) that we commonly, but unconsciously, use in our everyday involvement with "recognition." Such average, typical f-value, of consensus agreement, *can be* determined (as will be demonstrated). Thus, f, in Eq. (121), would be a constant for "general viewing" but would be a variable, when describing "particular situations."

The logic of the direct dependence of R_R on f, in Eq. (121), now becomes apparent. The relation says that increases in the feature size(s) of an object (increases in the f values) will result in corresponding increases in the recognition range.

To obtain approximate information about the discernment/recognition ranges and feature ratios involved in clear-air visibility, the author conducted a series of paperwork exercises and experiments to estimate the values for various situations.

The situations considered included cases of the discernment and recognition

1. of insects versus other insects or small objects,
2. of a cat versus a skunk versus a rock, and analogous cases,
3. of coin types contrasted against various backgrounds,
4. of a known person versus another,
5. of a human being versus other similar-size animals or objects,
6. of a buck deer from a doe—the hunter's problem,
7. of a road sign on the highway or in a city,

8. of various objects seen ahead while driving on a highway,
9. of objects viewed downward from a tall building,
10. of various types of aircraft flying aloft,
11. of various types of ships observed from the seashore,
12. of one city building from another observed from the ground,
13. of one particular mountain from another observed from the ground,
14. of a city feature observed from an aircraft or space vehicle,
15. of smaller features on the moon as opposed to larger features, as observed from the earth (without telescope),

all of these, plus other cases.*

From these subjective exercises, two ratio quantities were determined and "compensated" for the important effects of contrast. For example, one may assume that contrast, no matter what its value might be in a given situation, will be approximately the same for both discernment and recognition visibility. Moreover, one can deliberately (in the exercises) silhouette objects against a sky or other background of one's "mental choosing" and/or "adjust" a poor contrast condition into conformance with the optimum contrast value of $\ln(1/\epsilon) = 1.0$.

The discernment ratio, R_D/s, is by far the easier of the two ratios to assess. It was found, from the exercises, that the ratio had the approximate value

$$R_D/s \cong 3300 \quad \text{N.D.}, \tag{123}$$

*with an estimated subjective-departure-uncertainty of about ± 30 percent***.

The recognition ratio, R_R/s, was found to have the approximate value

$$R_R/s \cong 1200 \quad \text{N.D.}, \tag{124}$$

with an estimated subjective-departure-uncertainty of about ± 50 percent.

It follows from the approximations (123) and (124) that

$$R_D \cong 2.8\, R_R\,, \tag{125}$$

in any consistent length units of choice.

The approximate value of C, in Eq. (121), can now be ascertained from Eqs. (123), (124), and (125).

As mentioned earlier, the value of f, in Eq. (121), assumes its maximum value of f = 1.0 when the feature size of objects equals the "bulk size" of the objects themselves. Expressing this

* The author will not attempt to describe these "discernment and recognition exercises" beyond stating that they occupied his time over many days. He considered each case, individually, in fair depth, as objectively as possible, before drawing conclusions about the specific case. He also resorted to maps, personal measurements and experiments, journal and media items and just plain "common sense," in his attempts to convert the subjectivity of our universal viewing experiences into some form of "quantitivity."

** The constant here has a value close to the visual acuity limit (of optical theory) for distinguishing two black points on a white background as opposed to seeing them as one blended point. Thompson, (Harper and Row, NY, NY, 32nd Edition). The limiting, solid angle of view is 1/60° = 0.000291 radian, for which the above constant would be 3440.

another way that is equally true (but not precisely the same), when $f = 1.0$, an object may be "discerned" by its bulk size but it cannot be "recognized" by its features. Thus, for "discernment visibility in clear-air," Eq. (121) becomes

$$R_D = C\, s \ln(1/\epsilon) \quad \text{m}\,, \tag{126}$$

which, solved fo. ^, is

$$C = \frac{R_D}{s \ln(1/\epsilon)} \quad \text{N.D.} \tag{127}$$

If the discernment range of Eq. (123) is substituted into this equation, and if the contrast is assigned its maximum, *reference* value of $\ln(1/\epsilon) = 1.0$,

$$C \cong 3300 \quad \text{N.D.} \tag{128}$$

On the introduction of this value into Eq. (121),

$$R_R \cong 3300\, s\, f \ln(1/\epsilon) \quad \text{m}\,, \tag{129}$$

which is the approximate *general equation defining the recognition range* of objects in terms of object size, feature details, and contrast. This is the *first* of the final equations that will be illustrated.

When $f = 1.0$, in the above equation, it reduces to the approximate *general equation that defines the discernment range* of objects viewed, that is,

$$R_D \cong 3300\, s \ln(1/\epsilon) \quad \text{m}\,. \tag{130}$$

This is the *second* final equation to be illustrated.

The reader will intuit that there is an implied "f value," in Eq. (129), that corresponds to the author's work on his "discernment/recognition exercises." Indeed there is, and this value, from Eqs. (123) and (124), with reference to Eq. (129), has the approximate va!ue

$$f \cong \frac{R_R}{R_D} \cong 0.36 \quad \text{N.D.}\,, \tag{131}$$

which means that the recognition of an object under "average" viewing conditions requires that the features of the object should be roughly one third the overall size of the object.*

The three approximat: equations, Eqs. (123), (124), and (131), are obviously interrelated and all were considered in the recognition exercises, together with Eq. (121). It should additionally be noted that the feature ratio of recognition is not completely divorced from contrast differences that also enable recognition, particularly color contrasts (for example, recognizing various kinds of birds, or a wheat field from a corn field observed from a space vehicle, etc.).

* From optical theory, for the definition of 20/20 vision, $f = 0.20$.

To summarize findings to this point, Eq. (126) provides information about the "discernment range" of objects viewed in clear air and Eq. (129) provides information about the "recognition range" of the objects. Both equations are "object specific" and the discernment range for equivalent contrast conditions is 2.8 times greater than the recognition range.* The values of the constants are approximate, but useful nonetheless.

We may now consider how the discernment and recognition ranges can be defined for *cloudy* situations of the atmosphere, for which clear-air viewing become special limiting cases of maximum discernment *visibility* and maximum recognition *visibility*. It is necessary, symbolically, in equations and in practice, to differentiate between clear-air viewing, which will be referred to in terms of range (as has been the case thus far), and cloudy viewing, which will be referred to and symbolized in terms of visibility, with V_D being the discernment visibility and V being the recognition visibility. (The terms "range" and "visibility," here, are interchangeable, since visibility *is* a range quantity.)

A "tie" (or "tie point") may be established between the clear-air Eq. (130) written for the maximum discernment range ($\ln 1/\epsilon = 1.0$), that is,

$$R_{D_m} = 3300 \text{ s} \qquad \text{m} \tag{132}$$

and the equation for the maximum discernment visibility

$$V_{D_m} = \frac{46.8 \; r_M}{M^{0.73} \; r_A} , \tag{133}$$

which stems from Eq. (76) multiplied by 2.8 (reflecting the finding herein of $\epsilon_c = 0.06$, not Koschmieder's $\epsilon_0 = 0.02$ of theoretical perfection—see footnote, this page) and also written for $\ln(1/\epsilon) = 1.0$. Eq. (133), of course, incorporates the distribution function of Khrgian and Mazin.

The next step involved in the specification of a "tie point" between clear and cloudy visibility requires a definition of "clear-air." Fortunately, such a definition has already been provided in the form of the visibility condition called "unlimited." Consequently, clear-air visibility exists when the maximum discernment visibility, R_D, of Eq. (132), is

$$R_D = 30 \text{ miles} \cong 48{,}300 \qquad \text{m} . \tag{134}$$

This means, from Eq. (133), neglecting truncation, that, when $V_{D_m} = R_{D_m}$,

$$M_C = 7.43 \times 10^{-5} \qquad \text{g m}^{-3} . \tag{135}$$

* In Section 6.2, Eq. (55), it was demonstrated that the "visual ranges" for discernment viewing were, from the work of Koschmieder (loc. cit.), 3.91 times larger than the visibilities for recognition viewing. The work herein indicates that the difference factor is 2.8, not 3.91. Koschmieder stated that his "threshold of *perfect contrast*" value of ϵ was $\epsilon_0 = 0.02$, for which $\ln(1/\epsilon_0) = 3.91$. The work herein implies that the "threshold of *common experience*" (not the theoretically perfect condition of Koschmieder) is approximately $\epsilon_c = 0.06$, for which $\ln(1/\epsilon_c) = 2.8$. This corresponds precisely to the $\epsilon_c = 0.06$ value determined by Houghton[51] (1939). The entire subject of reference ϵ_c values has been discussed in Section 9.2 and will not be rediscussed here.

[51] Houghton, H.G. (1939) On the relation between visibility and the constitution of clouds and fog. *J. Aer. Sci.*, **6**:408-411.

where M_C is the LWC (or the mass content of aerosols, or a combination) that *defines* the clear-air state. It also means that the size of the object being viewed at this range is

$$s_C = 14.6 \quad \text{m} , \tag{136}$$

from Eq. (132).

The effect of the introduction of s into the equations for cloudy visibility will be, in essence, to "modify" the liquid water content entering Eq. (133) from M to

$$M_{mod} = K\, M\, s^{-1.37} \quad \text{g m}^{-3} . \tag{137}$$

The constant, K, as determined from the "clear-air tie point," at which M_{mod} = M and s = 14.6 m, is

$$K = 14.6^{1.37} = 39.4 , \tag{138}$$

which permits Eq. (137) to be written as

$$M_{mod} = 39.4\, M\, s^{-1.37} \quad \text{g m}^{-3} . \tag{139}$$

If this equation is introduced into Eq. (133), with M_{mod} replacing M,

$$V_{D_m} = \frac{46.8\, r_M}{(39.4\, M\, s^{-1.37})^{0.73}\, r_A} = \frac{3.20\, s\, r_M}{M^{0.73}\, r_A} \quad \text{m} , \tag{140}$$

which is the defining equation for the maximum discernment visibility.

This equation may be tested for authenticity. Thus, at the clear-air tie point, s = 14.6 m and $M = 7.43 \times 10^{-5}$, and the equation reduces to $V_{D_m} = 48{,}270\, r_M/r_A$ m, which is correct, within roundoff. For a LWC of M = 0.01 g m^{-3} (a dense cloud or fog) and an s = 0.3 m (1 ft), the equation predicts a maximum discernment visibility of 8.6 m (28 ft). Although this does not constitute proof of equation validity, per se, it certainly emphasizes that the equation functions in a "proper fashion." (It is difficult to establish irrefutable proof of validity when dealing with a clear-air equation under cloudy circumstances.)

The development of the other visibility equations for discernment and recognition proceeds rapidly following the development of Eq. (140).

By introducing the contrast and extinction-ratio terms into Eq. (140),

$$V_D = \frac{3.20\, s\, \ln(1/\epsilon)\, r_M}{k_\sigma\, M^{0.73}\, r_A} \quad \text{m} . \tag{141}$$

which is the *general equation for discernment visibility* (as opposed to *maximum* discernment visibility). This is the *third* equation to be illustrated.

By recalling that the maximum recognition visibility is 2.8 times smaller than the maximum discernment visibility, [see the footnote on page 57 following Eq. (135)], Eq. (140) converts to

$$V_m = \frac{1.15\, s\, r_M}{M^{0.73}\, r_A} \quad m . \tag{142}$$

By introducing the contrast, extinction-ratio and feature-ratio terms into this equation

$$V = \frac{1.15\, f\, s\, \ln(1/\epsilon)\, r_M}{k_{ir}\, M^{0.73}\, r_A} \quad m , \tag{143}$$

which is the *general equation for recognition visibility*. This is the *fourth* and last of the equations to be illustrated.

Because of the complexity of the final visibility results, the remainder of this section is organized in a very definite fashion that must be explained.

First, it is necessary to present nomograms that illustrate the properties of the four final visibility equations, [Eqs. (129), (130), (141), and (143)]. These properties and their interrelationships among the different equations simply cannot be described in words. For instance, consider that Eq. (143) is an equation of six unknowns (neglecting truncation), or, equivalently, it has "six degrees of freedom" or represents a domain of six dimensions. Any attempted description of such equation relative to the others mandates the use of nomograms plus words.

The table and figures summarizing the nature of the final equations are presented in a deliberate, sequential order and they are placed in this order in the last pages of the section, following the text and before the beginning of the next section concerning radar/lidar meteorology. A summary table, Table 6, is presented first. This outlines the types of visibility equations that have been developed, indicates the pertinent equation numbers and refers to the nomograms (by figure number) where the equation properties are illustrated. Moreover, the table reveals how the equations become simplified with the assumption of average, typical conditions of visibility and how they become further simplified, to their elementary states, with the specification of a fog or cloud of a given LWC.

Following the summary table, the descriptive diagrams/nomograms are presented in an order that proceeds generally from viewing conditions of largest range (discernment in clear air) to viewing conditions of smallest range (recognition in cloudy air). Two versions of each diagram/nomogram are offered, one scaled in meters and kilometers, for research purposes and users of the metric system of units, and another, scaled in inches, feet, and miles, for Americans schooled in the British system of units.

The diagram(s) of Figures 11 (or 12) illustrate the viewing situation of *discernment in clear air*, from Eq. (130). The only thing that acts to modify this situation (other than the size of the object) is the contrast between the object viewed and its immediate surroundings. The nomogram(s) of Figures 13 (or 14) reveal the situation of object *recognition in clear air*, from Eq. (129) using an average f = 0.36, corresponding to Eq. (131). Here, in addition to object size and contrast, the average feature details of objects viewed have been incorporated in the nomograms.

The nomograms of Figures 15–18 illustrate situations of viewing in *cloudy air**. With clouds present, the *extinction ratio* of the water droplets becomes a factor of visibility reduction that is nonexistent in clear air. Moreover, the number concentration and size distribution of the droplets become important. These factors have been parameterized herein through use of the Khrgian-Mazin distribution function and have been incorporated into the constant and the LWC term of Eqs. (141) and (143). Additionally, just as in clear-air viewing, object size and contrast are the major factors of *discernment* under cloudy circumstances and *recognition* visibility is reduced, relative to discernment visibility, by the value of the feature ratio that one chooses to define as recognition. The ratio is assumed to be 0.36 in the nomograms of Figures 15–18.

The diagrams of Figures 11 and 12, for clear-air discernment, and those of Figures 13 and 14, for clear-air recognition, require no instruction.

The nomograms for cloudy visibility (of discernment and recognition), of Figures 15–18, contain extra "parts" that incorporate the extinction-ratio term, k_{σ} at the lower right, and the s versus M relation of Eq. (140) at the left. All "diagram parts" of these nomograms are entered orthogonally with the specific quantities that are important to visibility. At the crossing point(s) of the orthogonal lines, tracing proceeds along the sloping tracing lines into the next "diagram part," or into the "main visibility diagram" located at the upper right. (The procedure is akin to the more-or-less-standard technique of a computer programmer, who "breaks a problem" into sub-routines that "feed" a main program.) It might also be noted that, in general, the diagram part on the lower right hand side of the nomogram serves to define the circumstances of viewing (that is, the contrast and extinction ratio) whereas the diagram part at left defines the LWC state of the clouds and documents the relations between object size and discernment or recognition visibility.

A few words about the design limits of the nomograms are also in order.

The clear-air diagrams/nomograms of Figures 11–12 and 13–14 have been extended, in design and plotting, to very-large visibility ranges, of some 36,000–100,000 km (22,000–62,000 mi), for discernment, which encompasses the space-vehicle and satellite viewing of earth objects (or the objects of other sun-planet systems) from distances as large as the earth-synchronous altitude of 22,000 mi (35,000 km). The viewing, from such ranges, is presumed to be that of a typical human being, with 20/20 eyesight, without employment of telescopic or other vision-enhancement aids. At the opposite extreme of small object size and small visual range, the clear-air diagrams/nomograms of the figures cited are limited to object sizes of about 0.001–0.01 m (0.04–0.4 in.), with corresponding visual ranges of about 1–4 m (3–13 ft).

The "cloud-state" nomograms of Figures 15–16 and 17–18 are limited, in *their* extremes, to a maximum discernment visibility of 30 miles (Figures 15–16), which is the definition of the clear-air state, and to a 10.7 mile maximum recognition visibility (Figures 17–18), which is 2.8 times smaller than the maximum discernment visibility. For ranges larger than these, we are involved in clear-air visibility, not cloudy visibility, and Figures 11–14 should be used for prediction rather than Figures 15–18. At the opposite, small-visibility extreme of Figures 15–18, the nomograms have design limits of M = 5 g m^{-3}, k_{σ} = 4.0, with V_D = 0.54 s and V = 0.068 s. The design limit on M will be exceeded in the viewing of very small objects (as in the insect example below). But Eqs. (141) and (143) are still valid and may be utilized in such cases, since M merely becomes a modi-

* Description of the actual construction details of these nomograms is beyond the scope of this report. Suffice it to say that the nomograms solve Eqs. (129), (130), (141), and (143), in parts, with important resort to equations (139) and (140).

fied, artificially-large, "effective M" and is not a real LWC value. The effects of earth curvature on visibility are ignored.

Now that the nature and limitations of the equations and nomograms have been briefly described, we may turn to a discussion of the significance of the equations concerning visibility in the atmosphere.

Perhaps the best way to demonstrate the descriptive power of the equation set [Eqs. (129), (130), (141), and (143)], relative to experience, is to present several examples of viewing situations that are predicted by the equations. This will also enable the reader to "check" the author's equation and nomographic evaluations. Six specific examples will be presented.

The first visibility situation to be considered is that of a fog/cloud of maximum visual obscuration. As noted previously, the maximum LWCs reported in the literature, that define such fog, are about 2 g m^{-3}. Thus, Eqs. (141) and (143), which specify the discernment and recognition of objects, become, for average, typical conditions of viewing [that is, contrast = 0.8, k_σ = 1.5 and f = 0.36, as assumed previously], V_D = 1.0 s and V = 0.13 s. If it is presumed that an intrepid motorist is looking for a large, overhead, directional-sign while "feeling" his/her way through this fog [sign size s ≅ 5 m (≅ 16 ft)], the sign should be vaguely discernable at a distance of 5 m (16 ft) and would only be recognizable at a distance of 0.7 m (2.3 ft). This says that the venturesome motorist, with the car directly beneath the sign, could "stand on the hood" and still not be able to recognize the lettering or information content of the sign.* The author has personally encountered fogs of such obscurement in Washington state, California, and the Ontario and Eastern Provinces of Canada. The reader has undoubtedly had similar experiences. The situations are real, not theoretical. Incidentally, on a clear day, with no obstructions ahead, the same large sign should be discernable, as a small "dot," at a range of 13 km (8 mi) and recognizable as a sign, with concentrated attention on the largest lettering, at a range of some 5 km (3 mi).

The second visibility situation for consideration is that of the outdoor discernment and recognition of an insect that draws our attention by its motion. Assume that the insect is crawling along a sidewalk and that average contrast conditions prevail, more or less. In clear air, Eq. (130) predicts that the insect (size = s ≅ 0.005 m ≅ 0.016 ft ≅ 0.2 in) can be discerned at a distance of 13 m (43 ft) and can be recognized (as being an ant, bee, fly, beetle, etc.) at a distance of 4.6 m (15 ft), from Eq. (129). This is viewing that also requires the deliberate attention of the observer. Now presume that the day is foggy, rather than clear. On such day, with a fog defined by a liquid water content of M = 0.001 g m^{-3} (a moderately dense fog), the observers discernment distance of the insect would be 1.3 m (4.3 ft), from Eq. (141), and his/her recognition distance would be ≅ 0.47 m (≅1.55 ft ≅ 18 in), from Eq. (143). (It should be noted that this situation lies beyond the "small-size limits" of the Figure 15–18 cloud nomograms.)

Third, consider the viewing situation of a motorist, who "looks ahead" on a highway for approaching traffic. She/he is able to discern a typical car (frontal, approaching size = s ≅ 1.5 m ≅ 5 ft) in clear air at a range of 4 km (2.5 mi), from Eq. (130), presuming the contrast = ln $(1/\epsilon)$ = 0.8. The motorist is able to recognize the car (the model, type and perhaps the manufacturer) at a range of 1.4 km (7/8 mi), from Eq. (129), presuming a feature ratio of 0.36. In comparison, under the moderate fog condition specified for the insect example above, the motor-

* This is an extreme case that can only be handled by Eqs. (141) and (143); it lies beyond the limits of the nomograms of Figures 15–18.

ist would only be able to discern the same approaching car at a range of 0.4 km (1/4 mi), from Eq. (141), and recognize it at a range of 51 m (167 ft), from Eq. (143). Moreover, if the motorist had been driving in the direction of the sun (but not directly toward it), as in early morning or late afternoon, his/her discernment and recognition distances might have been reduced by as much as a factor of 2, to 650 ft and 85 ft respectively.

Fourth, consider the situation of the ground viewing of a "hot air balloon," as it drifts with the wind toward an observer under average contrast conditions. The balloon (size s = 10 m = 30 ft) should be discernable, under clear-air conditions, as a "speck" in the sky, at a range of 26 km (16 mi), from Eq. (130), and should be recognizable, as perhaps belonging to a friend (by coloring, lettering, etc). at a range of 9.4 km (6 mi), from Eq. (129). On the other hand, under the moderate fog circumstances specified for the insect and motorist examples preceding, the discernment range of the balloon should be 2.6 km (1.6 mi), from Eq. (141), and the recognition distance should be 930 m (3050 ft), from Eq. (143).

The fifth example is lengthy and is designed to illustrate how the equations can be worked backward and forward to progressively obtain an answer. The situation involves air traffic safety and collision avoidance between two aircraft of different types flying "straight and level." One aircraft is a slow, light, single [s = 6 m, true airspeed (TAS) = 50 m s^{-1}] and the other is a fast, military jet (s = 10 m, TAS = 150 m s^{-1}). The light aircraft has a non-painted, aluminum fuselage and wings; the military jet has a fuselage and wings of conventional construction (aluminum, titanium, stainless steel, etc.). The day, at the flight altitudes of 10,500 feet and 10,000 feet, respectively, is quite hazy "with a light overcast" above. However, the ground-observer-reported visibility is the 1 mile required for visual-flight-rules (VFR), "heads up," "see and be seen" operations. The contrast between the aircraft and the haze-sky background is very small, say about 0.1. Their feature ratios are both about 0.36. The light aircraft, with a faulty altimeter, has drifted down to the flight altitude of the jet and the two aircraft on reciprocal headings are on collision course, with a closure rate of 200 m s^{-1}. Can the pilots, both alert and looking forward, avoid collision? If the observers report of the visibility was weighted for the recognition of a size distribution of objects of average contrast (0.8), then, from Eq. (143), for a recognition visibility of 1 mile (1609 m), with k_{dr} = 1.5, the hazy situation would correspond to an M value of approximately 0.0010 g m^{-3}. This same M value and conditions implies a discernment range of 2.8 miles (consistent with the 2.8 ratio between the two visibilities). An observer weighted toward the discernment of objects would have reported such a visibility. From this preliminary work with the equations, they may now be solved again for the flight conditions of the two aircraft pilots. The pilot of the light aircraft can first discern the presence of the larger jet (from the stated s and contrast values for the aircraft plus the k_{dr} = 1.5 and derived M values) at a distance of about 1300 feet (400 m, 2 seconds to impact), from Eq. 141, and can recognize it, with its f value = 0.36, at a distance of about 500 feet (150 m, 0.75 seconds to impact). The light plane, even if the pilot is extremely alert, cannot respond effectively to controls in a 0.75- to 2-second period. Disaster is certain. The pilot of the jet aircraft, moving faster and dealing with a smaller approaching object (the conditions have been stated) will discern the light aircraft 700 feet away (215 m, 1.1 seconds to impact) and recognize it at 250 feet (75 m, 0.4 seconds to impact) just before collision. This illustrates how a fatal encounter might occur under perfectly legal VFR conditions. The cause of the collision, of course, is that the light gray aircraft have so little contrast against the closely similar light gray background of the haze and sky.

Finally, let us return to the example of the deer hunter, which was employed to illustrate the difference between the generalized (historic) situation of discernment viewing and of recognition viewing. Let us consider how the "object specific" equations developed in this section quantify the prior generalities. The viewing circumstances of the deer hunter were that he/she was stalking a deer on a "dense-foggy" day, of LWC = 0.01 g m^{-3}, under rather poor contrast conditions, ln $(1/\epsilon)$ = 0.2, with a fog droplet extinction ratio assumed to be $k_\sigma = 1.5$. She/he was able to discern a living, moving object, perhaps a deer, at a range of 800 feet, but was only able to recognize that it was indeed a deer—and a legal buck as opposed to a doe—at a range of 200 feet. This was the prediction of the prior, generalized equations. The "object specific" equations of the present section permit a more-accurate prediction that may be stated in comparison. The deer (size = s ≅ 1.5 m ≅ 5 ft) should be discernable, from Eq. (141), or from the nomogram of Figure 15, as a moving, living object, at a range of 75 m ≅ 250 feet. The "feature" of the deer—antlers—that distinguishes a buck from a doe (s_f ≅ 1.5 ft, with a feature ratio of f ≅ 0.30) tells us that the deer hunter cannot realize his/her "killing quest" without creeping forward to a recognition range of 27 m ≅ 88 ft, as prescribed by Eq. (143) (the Figure 17 nomogram does not apply to an f value other than 0.36). This final example demonstrates how our previous, generalized visibility equations *grossly overpredict* our common, everyday experiences of viewing.

The six examples preceding are all predicted by the final visibility equations herein. The reader may judge whether the results make reasonable sense, or whether adjustments seem desirable to reflect better some "commonality of subjectivity," rather than just the author's own. *All* criticisms of *any* aspect of the present endeavor are *most* welcome. For it is only by working together, as a group, that we can hope to arrive at a quantitative assessment of subjectivity. Statements in the visibility literature have suggested that such a goal is impossible. The author does not share this pessimistic viewpoint.

Several additional comments are pertinent before moving on to the subject of radar/lidar meteorology.

The only way that cloudy visibility can be defined in *general* terms is by specifying the LWC of the cloud or fog. *Actual* viewing is always object specific and is confined to the discernment and recognition of objects such as cars, trucks, signs, buildings, hills, mountains, etc., which we view at different ranges under different contrast and other conditions. We mentally integrate and "average out" all of these multifarious views of objects and subjectively judge (*official* weather observers are included) that the general visibility is, "6 miles." But what does this "6 miles" really mean? What is it that the layman or aircraft pilot is supposed to discern or recognize at an officially reported visibility of "6 miles?" This is a presently unanswered question that the work herein may help resolve. For example, Equations (141) and (143) indicate that a report of 6 miles visibility under typical viewing conditions implies that the observer is mentally involved with the discernment of objects of about 5–17 m (16–54 ft) size and/or the recognition of objects of about 16–55 m (52–180 ft) size, whether she/he "knows it or not."

The average, "representative" visibility for a given site, is obtained, in today's practice, by viewing numerous objects surrounding a site and obtaining an impressionistic average for all objects, which is reported as the site or station visibility. From the findings herein, this reporting practice can be considerably improved by the thoughtful design of standardized "markers" that could be emplaced at known (surveyed) range(s) surrounding a site. [Natural objects simply *cannot* be used as reliable visibility references. For example, a "sky background" cannot be used

as a reliable contrast reference, since such background will depend on the "skycover" situation in the vicinity of the object being viewed. The background will vary from blue (no skycover) to dark gray (when the skycover is "thickly overcast"). This is one possible reason that Middleton (loc. cit.) obtained such large variation of ϵ_c values in his experiments with markers contrasted against the horizon. (See Section 9.2.)] It is suggested that a suitable marker, of careful design, might be manufactured that would insure constancy of background, contrast, and recognizability of features for visibility observations/measurements made either during the daytime or at night (if illuminated).

An uncertainty analysis was presented in Section 9.3 that concerned the matter of how accurately cloud LWC values might be estimated from visibility measurements. At the end of the section, it was suggested that "someting seemed to be missing" in the analysis and that "that something" might have been a failure to consider the subject of visibility in clear air and its relation to visibility in cloudy air. This led to the work of the present section.

With reference to this uncertainty analysis, it is now known that there are three additional factors of uncertainty involved in LWC assessment from visibility than were considered previously. The first is the range to an object. How accurately is this known? Is it estimated or measured? The second is the size of the object; is it estimated or known? The third is the feature ratio of the object that allows recognition. How, and how well, can this be defined and what level of feature detail do we choose to regard as recognition?

The conclusions of Section 9.3 (summarized in Table 5) remain relatively unchanged by the addition of these three factors to the visibility equations, since all are under our measurement/definition control. The range to objects viewed can be established to an accuracy such that uncertainty effects on visibility become negligible. The size of objects, although somewhat difficult to define in profile projection, can also be established with considerable accuracy. The definition of "recognition" lies completely under our control, hence is essentially devoid of uncertainty. Therefore, the conclusion that visibility observations or measurements provide excellent, accurate means of LWC determination stands unchanged.

This terminates the discussion of visibility. We turn now to the equally important subject of how the equations of the Khrgian-Mazin distribution function can contribute to the field of radar/lidar meteorology and how the results compare with previous studies. The section begins on page 74).

Table 6. Summary of visibility findings, reference text.

Visibility Situation	Equation Number in text	Equation	Illustrated by Figure Numbers	Equation for Average, Typical Viewing Conditions*	Equation Example for a Moderately-Dense Fog/Cloud of LWC = 0.001 g m^{-3}
CLEAR-AIR VISIBILITY					
Discernment Range (Visibility)	130	$R_D = 3300\ s\ \ln(1/\varepsilon)$	11 and 12	$R_D = 2640\ s$	Clear-Air, N.A.
Maximum Discernment Range	130	$R_{D_m} = 3300\ s$	11 and 12	$R_{D_m} = 3300\ s$	Clear-Air, N.A.
Recognition Range (Visibility)	129	$R_R = 3300\ s\ f\ \ln(1/\varepsilon)$	13 and 14	$R_R = 950\ s$	Clear-Air, N.A.
Maximum Recognition Range	129	$R_{R_m} = R_{D_M}/2.8 = 1180\ s$	13 and 14	$R_{R_m} = 1180\ s$	Clear-Air, N.A.
CLOUDY VISIBILITY					
Discernment Visibility (Range)	141	$V_D = \frac{3.20\ s\ \ln(1/\varepsilon)}{k_\sigma M^{0.73}} \frac{r_M}{r_A}$	15 and 16	$V_D = \frac{1.71\ s}{M^{0.73}}$	$V_D = 265\ s$
Maximum Discernment Visibility	140	$V_{D_m} = \frac{3.20\ s}{M^{0.73}} \frac{r_M}{r_A}$	15 and 16	$V_{D_m} = \frac{3.20\ s}{M^{0.73}}$	$V_{D_m} = 496\ s$
Recognition Visibility (Range)	143	$V = \frac{1.14\ f\ s\ \ln(1/\varepsilon)}{k_\sigma M^{0.73}} \frac{r_M}{r_A}$	17 and 18	$V = \frac{0.219\ s}{M^{0.73}}$	$V = 33.9\ s$
Maximum Recognition Visibility	142	$V_m = \frac{1.14\ s}{M^{0.73}} \frac{r_M}{r_A}$	17 and 18	$V_m = \frac{1.14\ s}{M^{0.73}}$	$V_m = 177\ s$

*Average, typical conditions are $f = 0.36$, $\ln(1/\varepsilon) = 0.8$ and $k_\sigma = 1.5$, with $r_A = r_M = 1.0$, neglecting truncation.

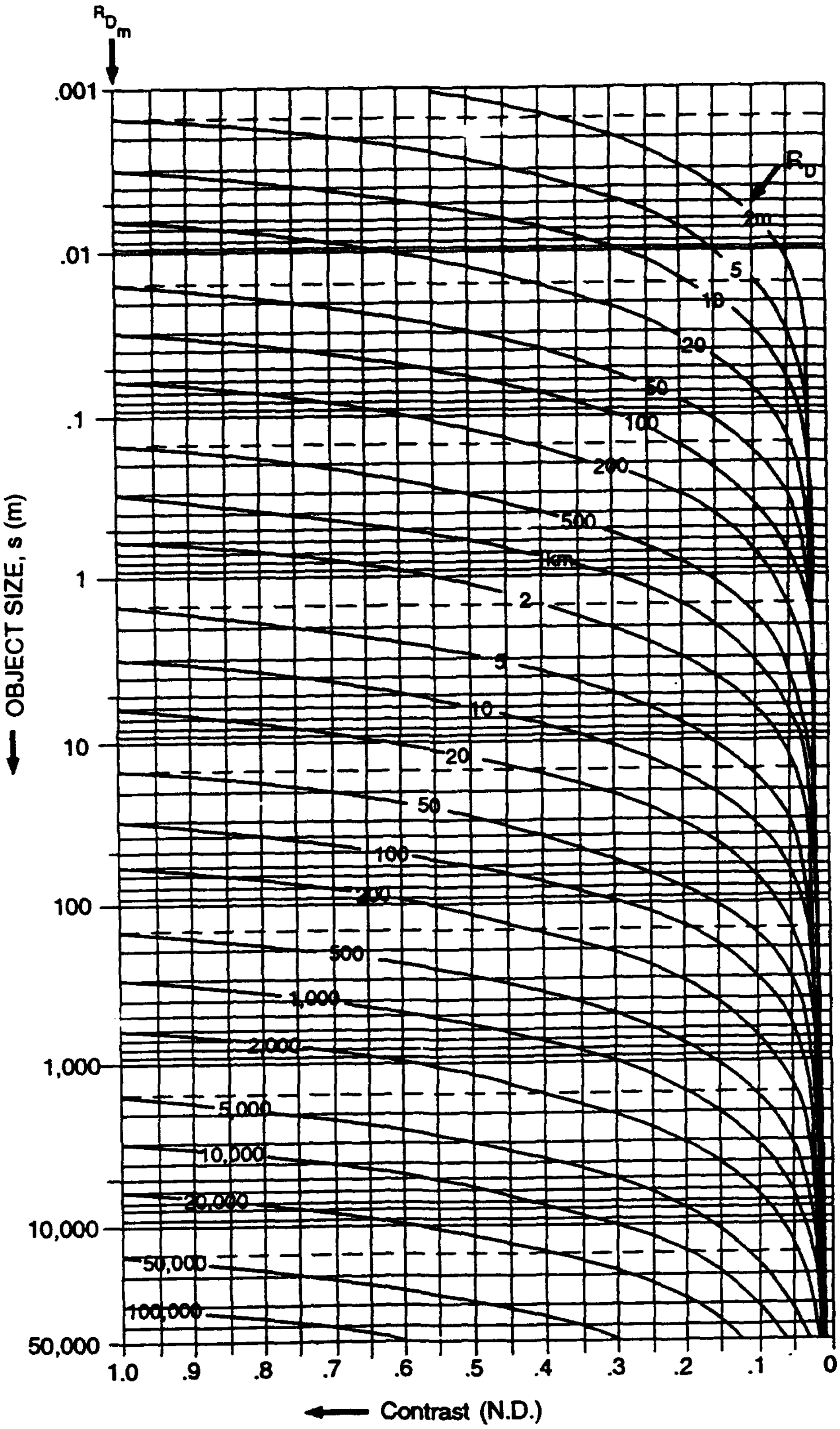


Figure 11. Discernment range in clear air with isolines in meters and kilometers

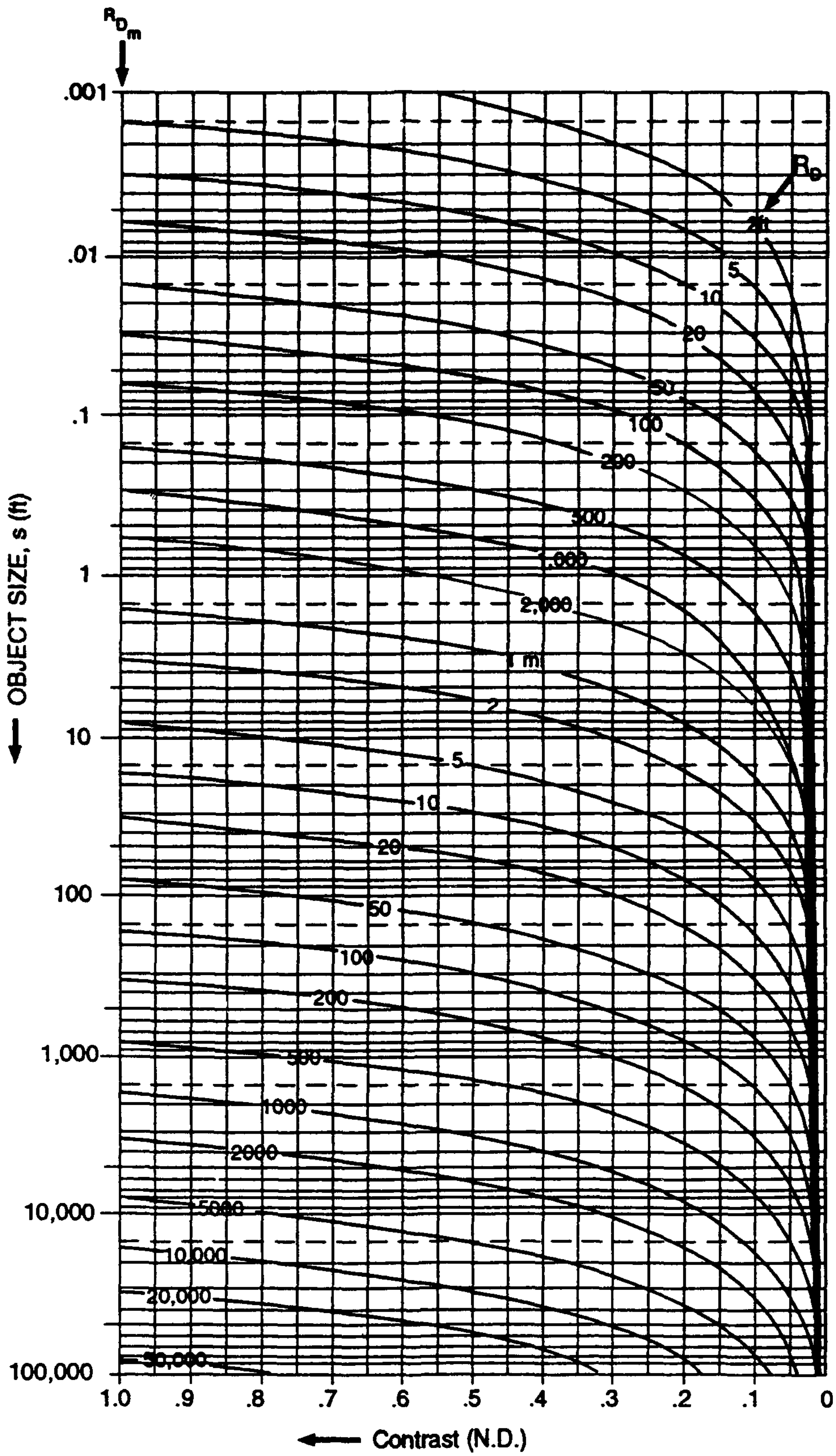


Figure 12. Discernment range in clear air with isolines in feet and miles

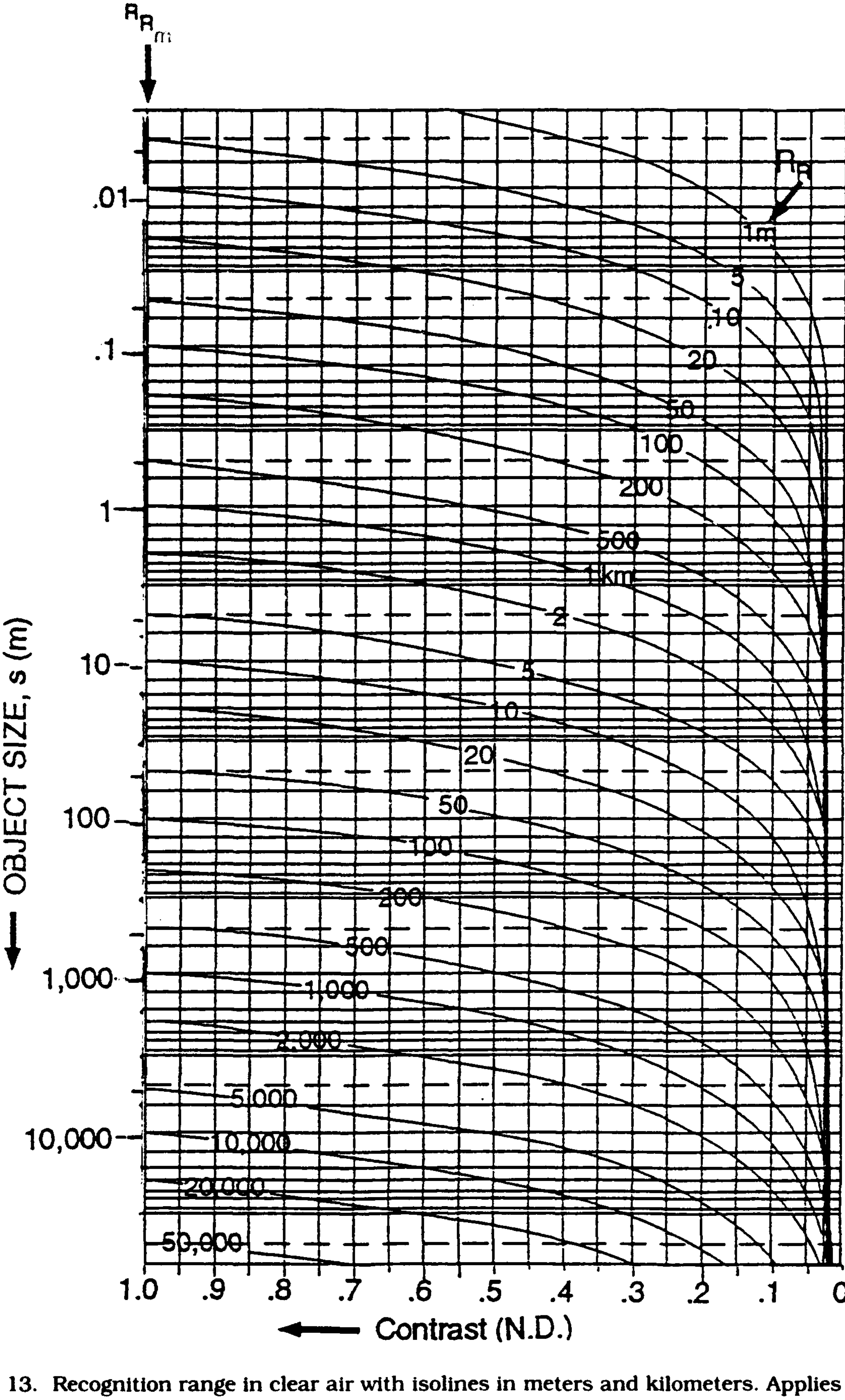


Figure 13. Recognition range in clear air with isolines in meters and kilometers. Applies to an average feature ratio of 0.36. (reference text).

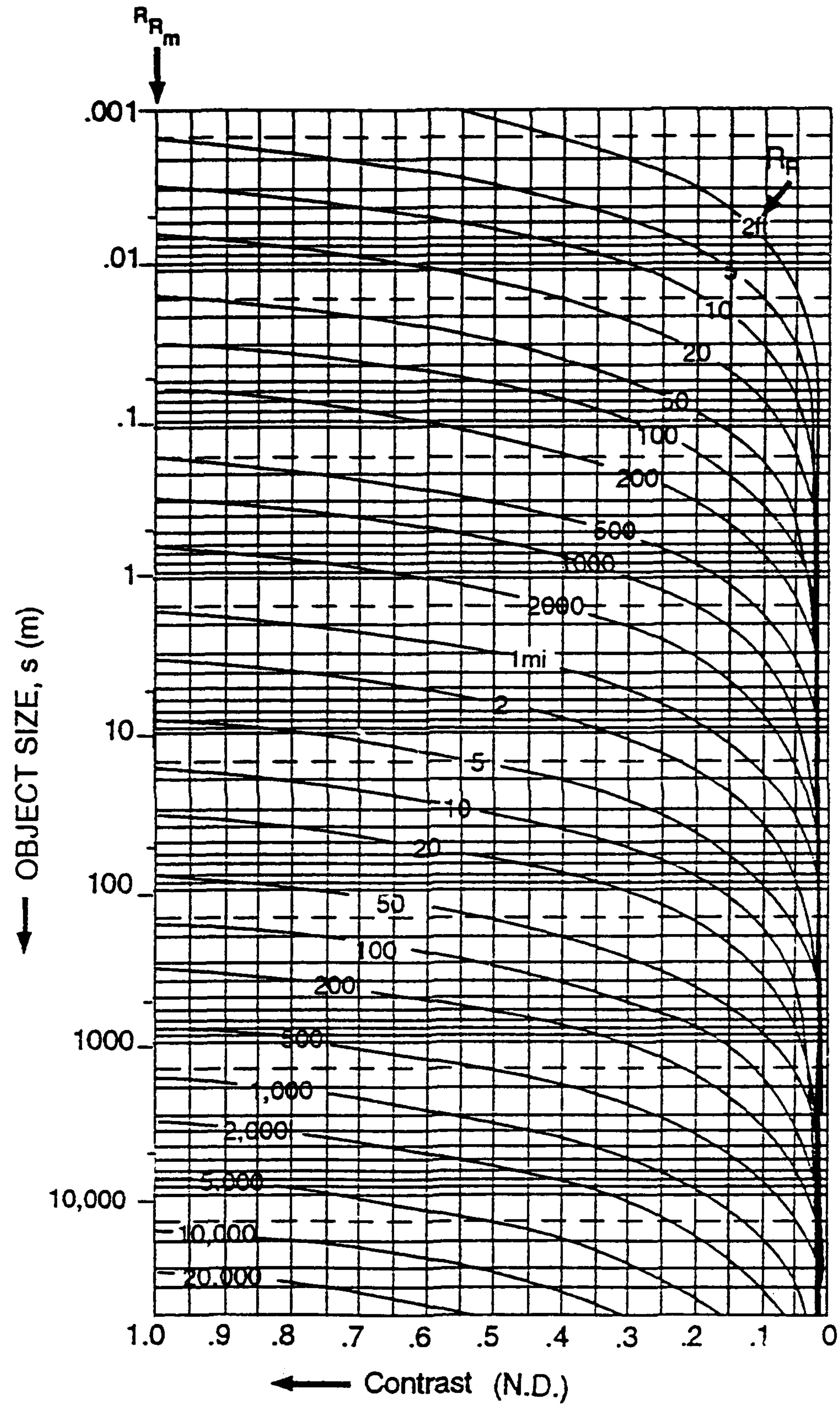


Figure 14. Recognition range in clear air with isolines in feet and miles. Applies to an average feature ratio of 0.36, (reference text).

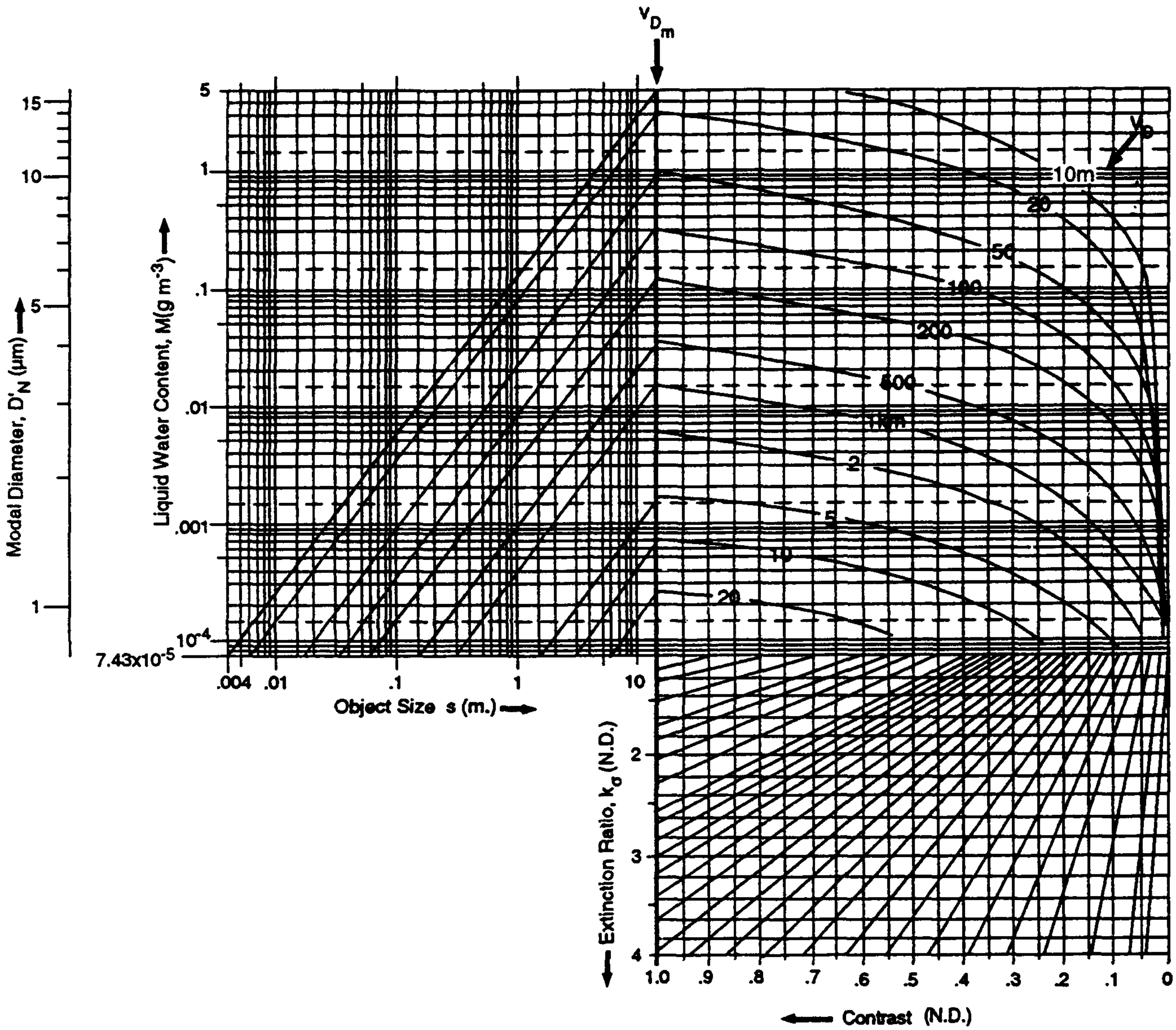


Figure 15. Discernment visibility in cloudy air with isolines in meters and kilometers

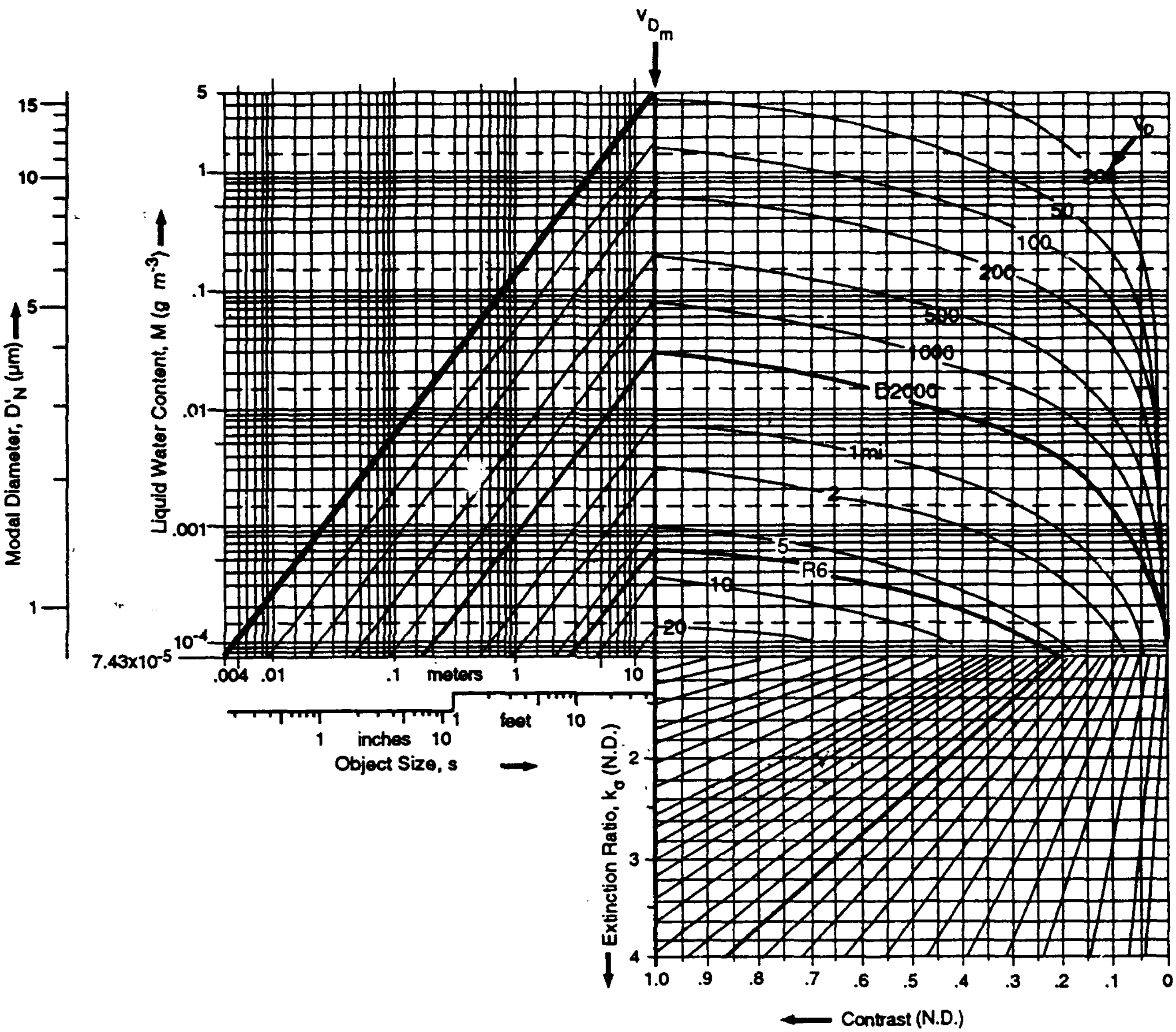


Figure 16. Discernment visibility in cloudy air with isolines in feet and miles

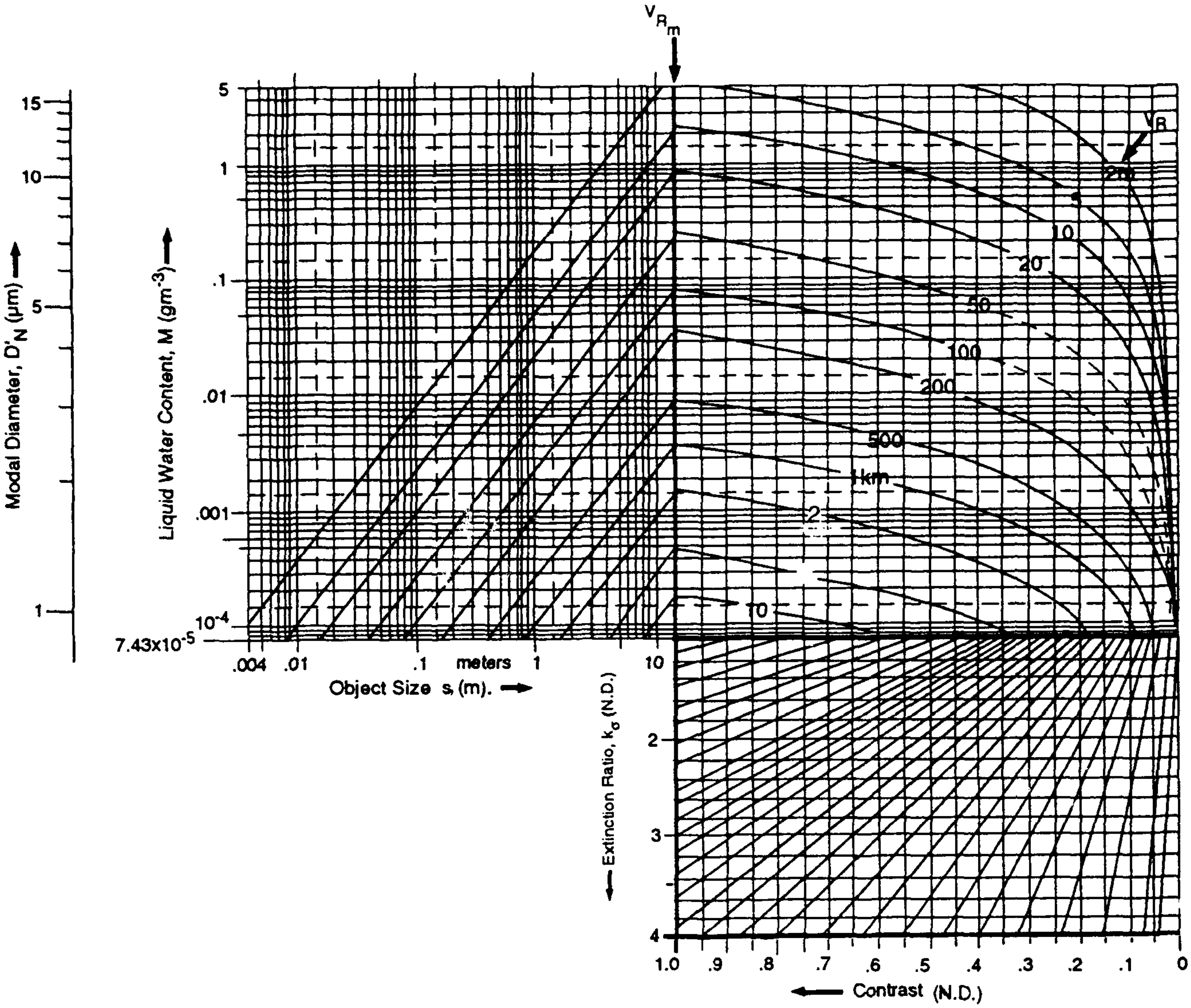
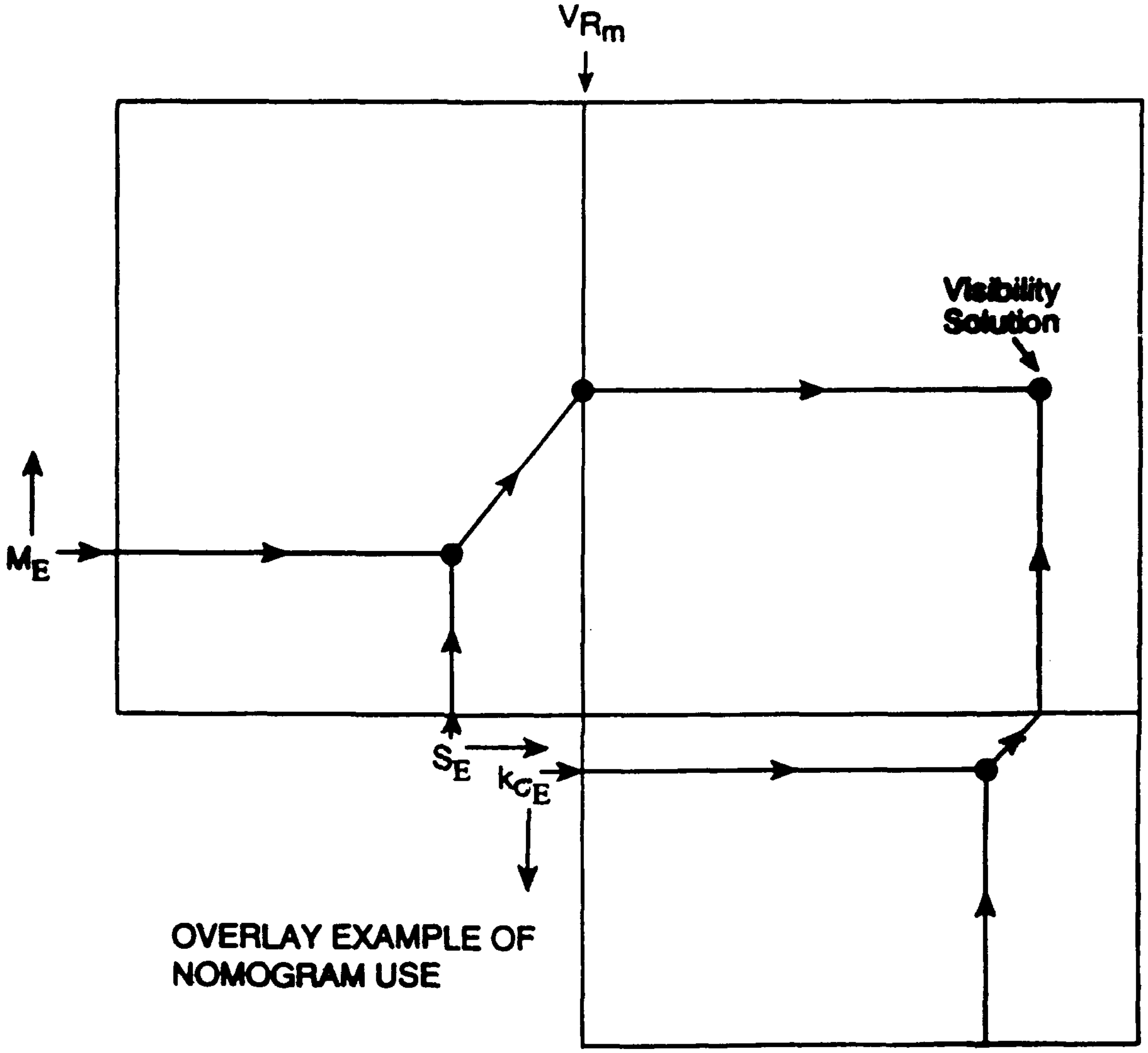


Figure 17. Recognition visibility in cloudy air with isolines in meters and kilometers. Applies to an average feature ratio of 0.36, reference text.



OVERLAY EXAMPLE OF NOMOGRAM USE

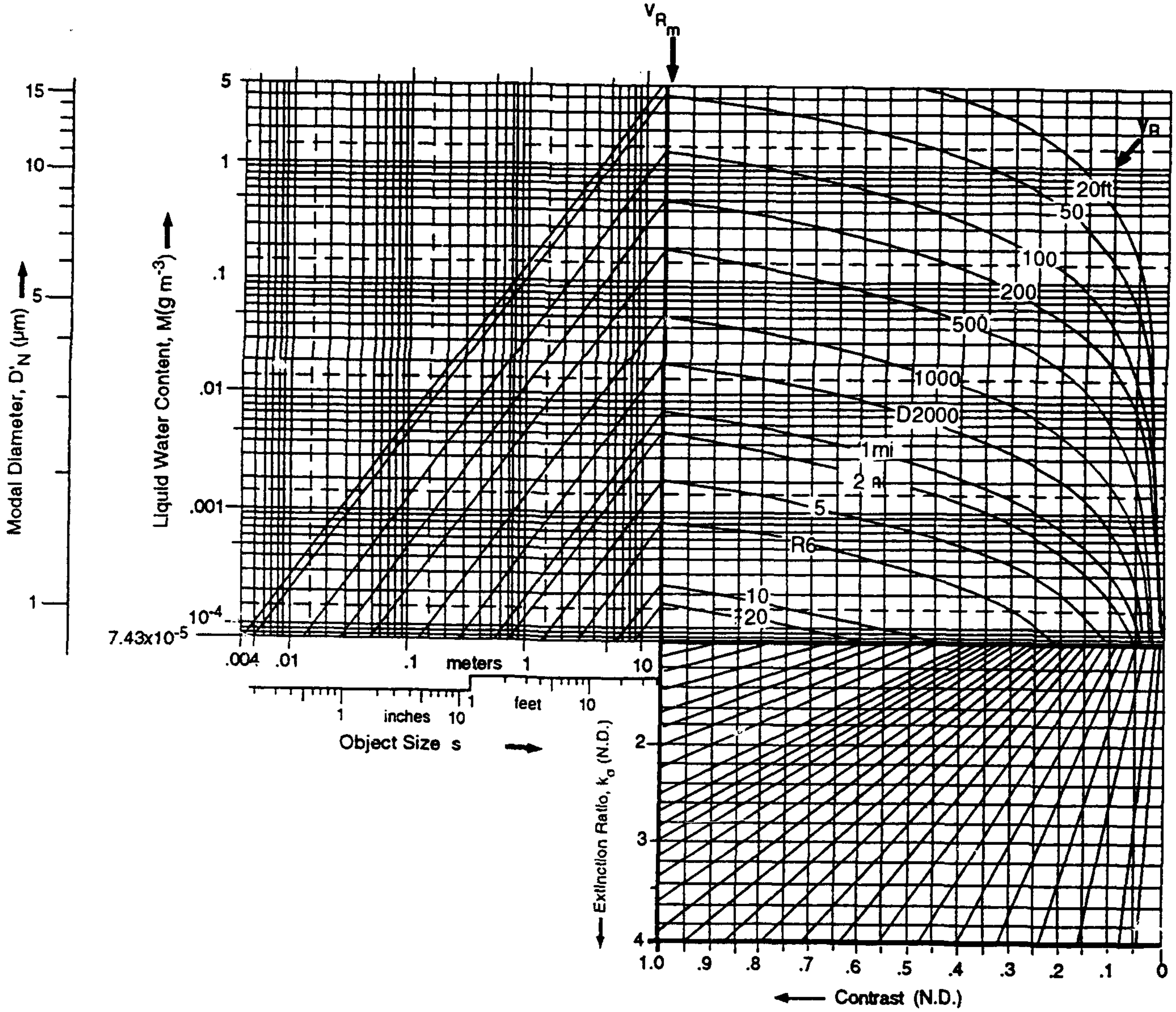


Figure 18. Recognition visibility in cloudy air with isolines in feet and miles. Applies to an average feature ratio of 0.36, reference text.

10. RADAR/LIDAR REFLECTIVITIES AND DATA COMPARISONS

The Khrgian-Mazin distribution function permits the establishment of relations among quantities that are important to radar/lidar meteorology. In this section, the M versus Z relation (of conventional expression) is developed for radar/lidar. The radar relation is next developed demonstrating how η (volume reflectivity) is dependent on Z (reflectivity factor). The equation is then used in comparison, for natural cloud types, with the measurements and equation work of prior investigations. The lidar equation relating η and Z is presented and discussed, relative to the same cloud types. Finally, the detection requirements of radars of different wavelength, and lidar, for natural clouds, are summarized in a table of "dBη requirement," which is the common form of η expression in the radar/lidar fields.

10.1 The M Versus Z Relation for Radar and Lidar Stemming from the KM Distribution Function

The radar/lidar reflectivity factor, Z, *is a function of the size spectra of the cloud droplets only.* Herein, the spectra are described by the basic KM distribution function.

The reflectivity factor may also be deduced indirectly from radar or lidar measurements. Since radars operate in the Rayleigh region of the Mie theory, the radar measurements are dependent on the wavelength of the transmitted radiation. Since most cloud lidars operate in the region of geometric optics of the Mie theory, the lidar measurements *are not* dependent on the wavelength of transmission.

The M versus Z relation *for both radar and lidar* is readily obtained from Eq. (73), by reversing the equation with the result

$$M = 4.02\ Z^{0.552} \left(\frac{r_M}{r_Z}\right)^{0.552} \quad g\ m^{-3}\ . \tag{144}$$

For persons well-versed in cloud and precipitation physics involving radar, it might be noted that the M versus Z relation found to be most descriptive *for rain*, from the AFGL, SAMS/ABRES Program, is

$$M = 0.00314\ Z^{0.576} \quad g\ m^{-3}\ . \tag{145}$$

This is the Joss, Thames and Waldvogel[63] (1968) equation for widespread rain, as also referenced and discussed by Plank[64] (1974b).

It is seen, neglecting truncation, that the exponents of the equations for water clouds and rain are quite similar. The coefficient for water clouds, however, is about 1300 times larger than that for rain, which reflects the fact that the Z values for water clouds are small, relative to rain (see Figure A4) but that the M values are, or can be (as shown in Figure A3) of comparable value. This emphasizes the descriptivity of Eq. (144).

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[63] Joss, J., Thames, J.C., and Waldvogel, A. (1968) The variation of raindrop size distributions at Locarno, *Proc. Internatl. Conf. on Cloud Physics*, Toronto, Amer. Meteor. Soc., Boston, 369.

[64] Plank, V.G. (1974) *Hydrometeor Parameters Determined from the Radar Data of the SAMS Rain Erosion Program. AFCRL/SAMS Report No. 2*, AFCRL-TR-74-0249, AD 786454, ERP No. 477, 86 pp.

10.2 The η versus Z Relations for Radars of Different Wavelength

The volume reflectivity, η, is the fundamental quantity measured by any "cloud physics radar." It is defined as the summation of the back-scatter return to the receiver, per unit illuminated volume of the radar. It is conventionally expressed in units of cm^{-1}.

Mason (1971) has presented the equation for water hydrometeors,[65]

$$\eta = \frac{0.93\,\pi^5\,Z}{\lambda^4}, \tag{146}$$

where λ is the wavelength of the radar. With units conversion, Plank (1974a), this becomes[66]

$$\eta = \frac{2.85 \times 10^{-10}\,Z}{\lambda^4} \quad cm^{-1}, \tag{147}$$

with λ still in cm.

10.3 η Values for Internationally-Defined Clouds for Radars of Different Wavelength, Plus Data Comparisons at X-Band

The average, typical liquid-water-contents for internationally-defined water clouds were determined in Section 9.2, Table 3, following the procedures explained therein. These averages are listed in Table 7, in the first data column of the table. The next two columns of the table show the Z values (from Eq. 73) and the η values (from Eq. (147)) for a radar wavelength of 1.25 cm.

Comparison measurements exist that were obtained by Plank, Atlas and Paulsen (1955) using a modified APS-34, X-Band radar with λ = 1.25 cm (or 24 Ghz frequency). The ranges of the measured η values for the internationally-defined clouds identified in Table 7 are presented in column 4 of the table. The corresponding value-ranges of Z, derived from Eq. (142) reversed, are supplied in the following column.

Atlas and Bartnoff (loc. cit.) have provided an equation for radar Z that may also be used in comparison. Without discussion of details, their equation is

$$Z = 1.91 \times 10^{-6}\,G(n)\,D_0^{\,3}\,M \qquad mm^6\,m^{-3}, \tag{148}$$

where D_0 is the median volume diameter of the cloud droplets, *in μm*, and G(n) is a non-dimensional quantity that is a function of the "spread" of the size distribution of the droplets. The Atlas-Bartnoff (AB) values of D_0 are listed in the first column of the "AB portion" of Table 7. These are the same values shown in Table 3 and explained in Section 9.2. The AB values of G(n) for the various identified types of internationally-defined water clouds are provided in the next column of the table and their Z values, and corresponding η values (from Eq. (142), for λ = 1.25 cm) are presented in the last columns of the table.

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[65] Mason, B.J. (1971) *The Physics of Clouds*, second edition, Clarendon Press, Oxford, England.

[66] Plank, V.G. (1974) *A Summary of the Radar Equations and Measurement Techniques Used in the SAMS Rain Erosion Program at Wallops Island, Virginia*. *AFCRL/SAMS Report No. 1*, AFCRL-TR-74-0053, Special Report No. 172, 108 pp., AD 778 095.

Table 7. Comparison of equation and measured values of radar Z and η for natural cloud types

Cloud Type	Average LWC M (g m^{-3})	Z from Equation (73) and Associated η: Z (mm^6 m^{-3})	η (cm^{-1})	η Values Measured by Plank, Atlas and Paulsen (1955): Typical η Range (cm^{-1})	Corresponding Range of Z (mm^6 m^{-3})	Z Values from Atlas and Bartnoff (1953) and Corresponding η's Reference Text: D_0 (μm)	G(n) (ND)	Z (mm^6 m^{-3})	η (cm^{-1})
Cumuliform									
Fair weather cumulus . . . Cu	0.346	0.012	1.4x10^{-12}	<2.5x10^{-12}	<.021	15.4	1.25	0.0087	1.0x10^{-12}
Stratocumulus . . . . Sc	0.439	0.018	2.1x10^{-12}	5.0x10^{-12}—1.0x10^{-10}	0.043—0.86	15.9	1.44	0.011	1.3x10^{-12}
Alto cumulus. . . . . Ac	0.736	0.046	5.4x10^{-12}	2.5x10^{-12}—2.0x10^{-10}	0.021—1.7	17.0	1.32	0.012	1.4x10^{-12}
Cumulus congestus . . . . Cg	1.12	0.099	1.2x10^{-11}	2.5x10^{-12}—5.0x10^{-10}	0.021—4.3	14.3	1.38	0.0077	9.0x10^{-11}
Stratiform									
Stratus . . . . St	0.363	0.013	1.6x10^{-12}	5.0x10^{-12}—2.5x10^{-11}	0.043—0.22	15.7	1.25	0.0092	1.1x10^{-12}
Alto stratus . . . . As	0.526	0.025	2.9x10^{-12}			17.0	1.32	0.012	1.4x10^{-12}
Translucidus . . . . As				2.5x10^{-12}—2.5x10^{-10}	0.021—2.2				
Opacus . . . . As	1.00	0.080	9.4x10^{-12}	1.0x10^{-11}—1.0x10^{-9}	0.086—8.6	17.0	1.32	0.012	1.4x10^{-12}
Nimbostratus . . . . Ns	1.52	0.17	2.0x10^{-11}	1.2x10^{-11}—1.5x10^{-9}	0.10—13	13.8	1.45	0.0048	5.6x10^{-13}

It is observed, from Table 7, that both the equations herein (H) and the AB equations predict Z and η values which, except for AB regarding Ns, tend to lie somewhat below or at the small value end of the PAP range of measured values. With regard to Ns, the H predictions lie within the measured range but those of AB do not. There is an obvious problem with the AB predictions which may have resulted from some kind of typographical error in their paper. Radar calibration unknowns also probably existed in the PAP measurements, which might explain why their value ranges seem "overly large."

In general, the H predictions and those of AB are in approximate "dBZ accord" (dBZ being the conventional radar-meteorological way of expressing Z). The H predicted values of Z, neglecting Ns clouds, are, on the average, about 4.8 times larger than those of AB. The dBZ values are about 5.3 times larger.

The first section of Table 8 shows the values of dBη that are required (according to the work herein) by radars of different wavelengths to detect the internationally-defined, water-cloud-types identified in the table. This reveals the general criteria for cloud detection by any radar operating in the wavelength (or frequency) bands defined as K-Band, X-Band, C-Band, S-Band and L-Band. The dBη values provided in the table are "as far as one can go," in specifying detection criteria, without full and complete knowledge of the characteristics of the particular radar system. (Such knowledge involves information about pulse width, pulse repetition frequency, transmitted power, minimum-detectable received power, chirping or frequency-sweeping techniques employed, pulse averaging or signal integration procedures used, "long term" time averaging possibilities, and whether the radar is of usual or phased-array type, etc.)

Casually, one would assume that radars of relatively large wavelength, C-Band or larger, would be useless in cloud detection. However, this neglects the fact that numerous operational radars today are extremely powerful and sophisticated. For example, Hardy and Katz[67](1969), Atlas, et al[68,69] (1966a, 1966b) and Atlas[70] (1990) using S band radars at the NASA. Wallops Island Facility were able to detect clouds with the radars. Gossard, Strauch and Rogers[71] (1990) were able to use an L-Band, vertically-pointing doppler radar to deduce the size distributions of cloud and precipitation. Blood (in Hardy, et al,[72] 1981) demonstrated theoretically that it was possible to detect very thin cirrus clouds at L-Band, using the Tradex-L radar (with chirp waveform) at the Kwajalein Missle Range. The technique required "long term" averaging (to integrate signal from noise) to deduce the nature of the cirrus. The coherent processing periods (during which the

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[67] Hardy, K.R., and Katz, I. (1969) Probing the clear atmosphere with high power, high resolution radars. *Proc. IEEE*, **57**:468–480.

[68] Atlas, D., Hardy, K.R., Glover, K.M., Katz, I., and Konrad, T.G. (1966) Tropopause detected by radar. *Science*, **153**:1110–1112.

[69] Atlas, D., Hardy, K.R., and Konrad, T.G. (1966) Radar detection of the tropopause and clear air turbulence. *Preprints, 12th Radar Meteorology Conf.*, Norman, OK, Amer. Meteor. Soc., 279–284.

[70] Atlas, D. (1990) Radar in meteorology: Battan memorial and 40th anniversary radar meteorology conference. Amer. Meteor. Soc., Boston.

[71] Gossard, E.E., Strauch, R.G., and Rogers, R.R. (1990) Morphology of dropsize evolution in liquid precipitation observed by ground-based doppler radar. *Conf. on Cloud Physics*, Amer. Meteor. Soc., 419–426.

[72] Hardy, K.R., Blood, D.W., Bussey, A.J., Burke, H.K., Crane, R.K., and Tung, S.L. (1981) *Study of Meteorological Conditions Along Actual or Proposed Reentry Trajectories*. AFGL-TR-81-0184, 77 pp.

Table 8. Required dBη values for the detection of water clouds with K-Band, X-Band, C-Band, S-Band and L-Band radars, also Lidar.

Cloud Type	Radar Reflectivity Factor Z $mm^6\ m^{-3}$	Radar Reflectivity Factor dBZ	Required Detection Values: K-Band 0.[illegible] cm (35 Ghz) dBη	X-Band 1.25 cm (24 Ghz) dBη	X-Band 3.25 cm (9 Ghz) dBη	C-Band 6 cm (5 Ghz) dBη	S-Band 10 cm (3 Ghz) dBη	L-Band 20 cm (1.5 Ghz) dBη	Lidar (Visible-UV) dBη
Cumuliform									
Fair weather cumulus . . Cu	0.012	-19.2	-112	-119	-135	-146	-155	167	-38.6
Stratocumulus . . . . . . Sc	0.018	-17.4	-110	-117	-133	-144	-153	-165	-37.8
Alto cumulus . . . . Ac	0.046	-13.4	-106	-113	-129	-140	-149	-161	-36.2
Cumulus congestus . . . Cg	0.099	-10.0	-103	-110	-126	-137	-145	-158	-34.9
Stratiform									
Stratus . . . . St	0.013	-18.9	-112	-118	-135	-145	-154	-166	-38.4
Alto str[illegible] . . . . As	0.025	-16.0	-109	-115	-132	-143	-151	-164	-37.3
Trans[illegible]cidus . . . . As									
Op[illegible] . . . . As	0.080	-11.0	-104	-110	-127	-138	-146	-158	-35.2
Nimbostratus . . . . Ns	0.17	-7.7	-101	-107	-124	-134	-143	-155	-33.9

radar would remain focused at a particular "spot" at the cirrus altitude) were of the order of a minute. Unfortunately the Blood proposal was never tested.

The preceding paragraph explains why the author includes all radar bands [except W-Band (0.32 cm), which is dominated by Mie scattering (ref. Appendix B)] in his Table 8 specifications of the required dBη values for water cloud detection. (The detection criteria can, and have been, extended to "ice clouds," but this is beyond the scope of the present report.)

10.4 The η versus Z Relation for Lidars

Lidars employed for cloud detection operate mostly in the visible portion of the electromagnetic spectrum. They can also operate successfully in the ultraviolet portion. In both cases, the illuminating frequencies and cloud sizes to be detected lie within the region of geometric optics of the Mie theory, [reference Appendix B]. Clouds can also be detected within the infrared portion of the spectrum, but with considerably more difficulty, since such illumination of clouds occurs within the oscillatory Mie region of his general theory.

Only visible and UV illumination are considered in this section, and it is presumed that the particular lidar wavelengths have been chosen to avoid absorption lines of atmospheric gases.

The definition of the volume reflectivity for lidar is the same as for radar. It is the summation of the "back scatter" per unit illuminated pulse-volume. Thus, to a rough first approximation

$$\eta_L \cong (k_\sigma - 1)\,A\,, \qquad (149)$$

where k_σ is the extinction ratio and A is the projected, cross-sectional area of the cloud droplets in the direction of illumination.* For the KM distribution, A is given by Eq. (66), which, when introduced into Eq. (149), with length units conversion, yields

$$\eta_L \cong 0.00060\,(k_\sigma - 1)\,M^{0.73}\,\frac{r_A}{r_M} \quad \mathrm{cm}^{-1}\,. \qquad (150)$$

If Eq. (139) is introduced into the above equation,

$$\eta_L \cong 0.00166\,(k_\sigma - 1)\,Z^{0.403}\,\frac{r_A}{(r_M\,r_Z)^{0.597}} \quad \mathrm{cm}^{-1}\,. \qquad (151)$$

It was previously mentioned that, in the author's best judgment, k_σ is likely to have a value of about 1.5. With this value inserted into Eq. (151), and ignoring the truncation terms,

$$\eta_L \cong 8.30 \times 10^{-4}\,Z^{0.403} \quad \mathrm{cm}^{-1}\,. \qquad (152)$$

For the Z values for internationally-defined water clouds listed in Table 8, the dBη values required for lidar detection of the clouds at visible and UV wavelengths were computed from Eq. (152). They are shown in the last column of the table and are presented without comment.

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* This is "very approximate," since it ignores energy diversion by "side-scattering" and also ignores secondary diffractive, reflective and scattering effects. Eq. (149) is indicative only.

We now turn to a consideration of relations among the KM quantities other than the ones already discussed in Sections 5–10.

11. OTHER RELATIONS AMONG THE K-M QUANTITIES

In this report, *some* of the "more interesting" relations among cloud physics quantities that stem from the Khrgian-Mazin distribution function have been examined. But the surface has merely been touched concerning *other* valuable relations.

The matrtix diagram at the left in Figure 19 shows the totality of *all* possible relations among the quantities, N, A, V, M, and Z, of cloud physics interest. The matrix, in conformance with conventional plotting tradition, indicates the presumed independent (measured) "X" quantities (N, A, V, M, or Z) along its horizontal, abscissa direction and the (also presumed) dependent (estimated) "Y" quantities (N, A, V, M, or Z) along its vertical, ordinate direction. The matrix shows that there are 20 posible relations, which, by row translation, are specifically identified in the second matrix of Figure 19, at the right.

It may be stated that *none* of these twenty relations are devoid of cloud physics interest. Each has conceivable application, either now or with anticipated development of new instrumental methods of measurement. However, the author's resources simply do not permit discussion of all. He can merely indicate the relations that have been discussed herein (to a degree), those that seem "most interesting" for future study, and those that appear to have little immediate application without advancements in instrumentation or demonstrated operational needs.

Before proceeding, it should be noted that the particular relations of the right hand matrix of Figure 19 have been assigned the numbers 1 through 20, as typed in the upper right hand corners of the matrix blocks. This is for convenience of reference.,

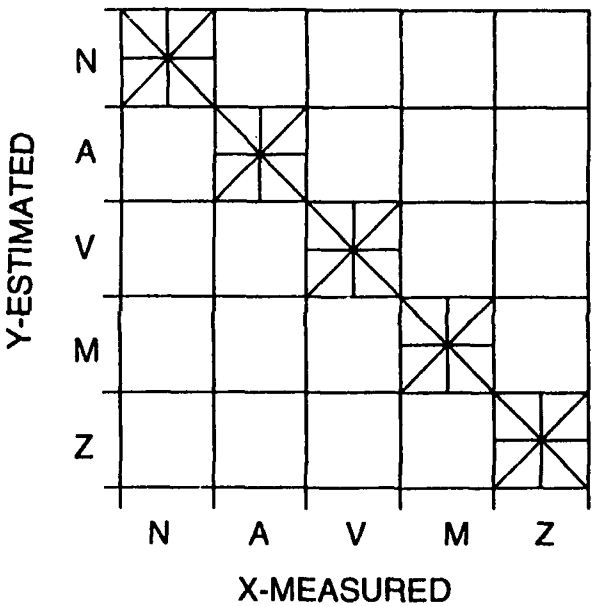
The particular relations of Figure 19 for which equations have been presented or which have been utilized or discussed herein are indicated by the screening material. These encompass the relations 3, 7, 10, 11, 15, 16 and 20, that involve all dependencies on M, the dependency of V on A, and the M versus Z relation. The most fascinating relation of all involves the distinct possibility of accurate LWC determination from observations or measurements of visibility.

Of the 14 remaining relations, those of estimating V from Z (for predicting visibilities aloft) and of estimating N from Z (for weather definition purposes) would seem most worthy of attention. Also of interest are all relations enabling an estimation of A, namely numbers 5–8, since A is a fundamental parameter of much extinction, attenuation and scattering work in the visual, radio/radar, IR and UV regions of the electromagnetic spectrum.

The author cannot conceive of any immediate. worthwhile applications for the other 7 relations (1, 2, 9, 13, 14, 17, and 18) but perhaps others can. Besides, who knows what the future might hold?

It should be noted and emphasized (as the most important accomplishment of this report) that any single, accurate measurement of *any* of the five quantities, N, A, V, M, or Z, enables estimates of the four other quantities not measured, *plus information about the distribution properties of all quantities.* For example, suppose that we have a single, accurate measurement of radar Z. From the relations 8, 12, and 16, we then have good estimates of the quantities A, V, and M. This, in turn, through any of the matrix relations, 1, 2, 3, or 4, provides estimates of N. The size

MATRIX DIAGRAM OF
ALL POSSIBLE RELATIONS



ROW # — SPECIFIC RELATIONS OF ESTIMATED Y FROM MEASURED X

ROW #				
1	N fm A (1)	N fm V (2)	N fm M (3)	N fm Z (4)
2	A " N (5)	A " V (6)	A " M (7)	A " Z (8)
3	V " N (9)	V " A (10)	V " M (11)	V " Z (12)
4	M " N (13)	M " A (14)	M " V (15)	M " Z (16)
5	Z " N (17)	Z " A (18)	Z " V (19)	Z " M (20)

Figure 19. Matrix diagram demonstrating all possible relations among quantities stemming from the KM distribution function together with second diagram identifying the relations

distribution properties of N_D, A_D, M_D, and Z_D are then prescribed by Eqs. (60), (64), (68) and (71). (Visibility, although not excluded, is a more complicated, "special case," regarding its distributed characteristics.)

What can be accomplished from this example of a single measurement applies equally well (within measurement uncertainty bounds) to any of the other quantities. Thus, from one, there results "all."

Of course, the validity of the above statements are based completely on the inherent descriptivity of the Khrgian-Mazin distribution function, or of the "Gamma Function."

It might be contended that some other distribution function, the normal, log-normal, Poisson, etc., might provide superior descriptivity in particular instances. This might very well be true, but it should be pointed out that, to provide this across-the-full-range-of-cloud-physics interest, any proposed function must be differentiable and integrable for all of the diameter moments of the quantities cited above (plus aerosols, desirably). Few functions can provide such capability without impossible or horrendous mathematical complexity.

Hence, although use of the Gamma Function, as herein, might cause some "descriptive lacks" in specific cases (even though none has been demonstrated to date) the overall, descriptivity of the function (including that of Appendix A) has considerable merit. In fact, in the author's opinion, this function (plus logical extensions) seems to be the natural, empirical descriptor of most of the cloud physics/precipitation events of the atmosphere.

A *warning* must be given, here, however. The equations of the present report *do not apply to, nor are they necessarily descriptive of*, cloud physics situations of active development or rapid dissipation. The equations have no growth or dissipative terms. They could be extended to contain such terms but this is completely beyond the scope of this report. The equations can also be extended to be the descriptor(s) of ice-crystal clouds and snow, but, this again, lies beyond the scope of the present report.

12. SUMMARY

Equations for double-truncated distributions and for totals were developed that describe the spectral and integrated properties of the number concentration, cross-sectional area, visibility, liquid water content, and radar/lidar reflectivity factor of water clouds in the atmosphere. These equations are all diameter moments of the "Gamma Function," as related, or "tied," to the basic, second-moment, distribution-function of Khrgian-Mazin (KM). The KM function, from extensive data comparisons, is highly descriptive of the number concentration of cloud droplets versus droplet diameter.

The truncation terms of the equations were discussed and examples of their utility in assessing the measurement capabilities and limitations of cloud physics instruments were presented and illustrated.

The method used to solve the equation, which essentially involves the expression of all distributed and totals quantities in terms of the modal diameter for number concentration and the total LWC of the cloud droplets, was explained. The basic nature of the KM distribution function, as being part of the general family of the Gamma Function, was noted and several applications of

the function to weather definition and to providing a continuity basis for storm models, were highlighted.

The equations for the summed cross-sectional areas of cloud droplets were converted into terms of visibility and the two types of visibility—discernment viewing at long ranges and recognition viewing at shorter ranges— were emphasized as being an intrinsic part of the common seeing experiences shared by all planetary creatures with eyes.

The history of visibility theory was recounted, as was the unfortunate stagnation of the theory from about 1931 to present. This stagnation (or "sidetracking") was due, in the author's opinion, to the failure of early researchers to "connect," "combine" and "build on" the works of Helmholtz[32] (1896), Trabert[28] (1901) and Koschmieder[29,30] (1924a, 1924b). Koschmieder's contributions are especially valuable since they explain the important (and often dominating) influence of contrast on visibility.

Visibility and LWC in water clouds of the atmosphere are sensitively related. One essentially defines the other. Moreover, as visibilities increase (or LWCs decrease) there is a basic association and merging of the smallest cloud droplets into the general populations of condensation nuclei, moist aerosols, dry aerosols, and polar molecules [which are ever-present constituents of the lower atmosphere that are generated by diverse sources and are secondarily governed, in their number concentrations and mass contents, by the relative humidity state and structure of the atmosphere (which, in turn, is dependent on the synoptic weather situation of a given day)].

Such considerations, of a logical merger of the smallest cloud droplets (of visibility) with the aerosols (of haze, dust, or smog situations), led to an equation assumption of "merger," which *recognized that, for a common* bandwidth, the number concentration of particles will decrease with decreasing size (see Figure 6 for N total) and that the LWCs (or mass contents) will be likewise reduced. This assumption (or relation between modal diameter and LWC) mandated changes in *all* equations of the KM distribution function that had been written theretofore.

The visibility situations of discernment and recognition were described and illustrated by use of nomograms. Comparisons were made with previous visibility studies and examples were cited to relate equation results to common, everyday experiences of viewing.

An uncertainty analysis was undertaken to demonstrate the versatility of the KM equations and to ascertain how well LWC might be determined from measurements of visibility. The answer was to about ± 50 percent, for LWC values ranging from 10^{-5} to 2 g m^{-3}. However, more important than *this answer* was the suspicion engendered by the work that certain factors significant to visibility had been neglected, historically, and were still being neglected, presently, in the general theory of visibility. It was postulated that the missing factors involved the definition and equation expression of visibility in clear air, *together with* their expression for cloudy air, *as well as* considerations about the nature of the "link" between the two.

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[32] Helmholtz, H.L.F. von (1896) *Handbuch der Physiologischen Optik*. Hamburg und Leipzig.

[28] Trabert, Wilhelm (1901) Die extinction des lichtes in einem truben medium (Schweite in wolken). *Meteor. Z.*, **18**:518-525.

[29] Koschmieder, H. (1924) Theorie der horizontalen sichtweite. *Beiträge zur physik der freien atmosphäre*, **XII**:33-53.

[30] Koschmieder, H. (1924b) Theorie der horizontalen sichtweite II: kontrast und sichtweite. *Beitrage zur physik der freien atmosphare*, **XII**:171-181.

Equations were developed and presented describing the *discernment* of objects of various sizes in clear air and the *recognition* of objects in clear air. Clear air was defined as the synoptic state of unlimited visibility (≥ 30 miles). This enabled the previous visibility equations for cloudy air to also be written in terms of discernment and recognition visibility. Various examples of the descriptive power of the new, more-generalized equations were offered and discussed. A set of predictive nomograms was provided.

The implications of the Khrgian-Mazin distribution function in the fields of radar and lidar meteorology were considered next. The KM equation for the radar reflectivity factor (Z) was presented and its relation to volume reflectivity (η) was noted. A so-called M vs Z relation for water clouds was developed as were η vs Z relations for radar and, very tentatively, for lidar. The KM predictions of η and Z for internationally-defined, natural water-clouds were compared with the Plank, Atlas and Paulsen[73] (1955) X-Band measurements of η for such clouds. Comparisons were also made with the predictive equations of Atlas and Bartnoff[56] (1953). The nominal detectabilities of these natural clouds, in terms of dBη and for radar wavelengths from K-Band to L-Band (also lidar—tentatively), were explained and tabulated.

The totality of the associative (governing) relations among KM quantities of cloud physics interest was pointed out and emphasized. Of the twenty total, it was noted that only seven had been discussed specifically in the present report (due to necessary restrictions of scope). However, *all* KM associations among the cloud physics quantities were deemed quantitatively and operationally useful, if not now, then sometime in the foreseeable future. Some of the most promising possibilities were cited. The KM function and associations were mentioned as providing a sort of "continuity equation" for cloud physics, which prescribes conditions that are usually true for any given point of atmospheric space, but which, with processes of cloud development and dissipation can depart significantly from such state (unless time-change terms were to be incorporated into the equations).

Three appendixes are included as part of the report. Appendix A outlines how the separate empirical findings in the diverse fields of aerosol physics, cloud physics, precipitation physics, and visibility, can, if consolidated on a common comparison basis, provide valuable insight concerning the overall nature of precipitation development in the atmosphere. Text and illustrative examples of such possibilities are provided. It was noted that these composite relations and equations are important (1) to the understanding of value consistencies and differences among quantities when compared on a common basis, (2) to "weather definition," which requires predictive ability of particle sizes, and other quantities, over a broad range of concern and (3) to storm-model continuity and consistency (for checking existing models and planning new ones).

Appendix B considers the Mie scattering theory and how different wavelengths of illumination impinging on different size distributions of aerosols and hydrometeors would be effected by the theory. Appendix C indicates how a *monodispersed* population of cloud droplets, differing radically from the KM distribution, would affect visibility and other quantities.

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[73] Plank, V.G., Atlas, D., and Paulsen, W.H. (1955) The nature and detectability of clouds and precipitation as determined by 1.25 centimeter radar. *J. Meteor.*, **12**:358–378

[56] Atlas, D., and Bartnoff, S. (1953) Cloud visibility, radar reflectivity and drop-size distribution. *J. Meteor.*, **10**:143–148.

The entirety of the report was dedicated to discussion and demonstration of how well the Khrgian-Mazin equations describe the physics of cloud events in various fields of endeavor and to how easily they can be incorporated with other equations or consolidated to yield new insights.

13. CONCLUSIONS

A thesis was advanced at the beginning of the report that the Khrgian-Mazin distribution function and its associated moments of the general Gamma Function had sweeping implications across a broad range of cloud physics concern in various fields of endeavor. From the basic and comparative work herein, it is suggested that this thesis has now been verified.

The most important conclusion is that the KM function provides a quantitative mathematical connection among the total and distributed properties of five quantities important to cloud physics: number-concentration, cross-sectional-area, visibility, liquid-water-content, and radar/lidar-reflectivity-factor. It also permits a quantitative association with the historical size-distribution equations of precipitation physics and is compatible with certain of the descriptor equations for the dry and moist aerosols of the atmosphere. Thus, it becomes possible to write consistent, consolidated equations covering the full size range of aerosols, water clouds and rain. An extension to ice clouds and snow is also possible with continued work.

The properties of water clouds are indelibly tied to visibility and visibility theory. For this reason, the report concentrated predominantly on this subject and important results ensued. Visibility theory was extended to include considerations of droplet-size-distribution, LWC, contrast, extinction-ratio, object-size and feature-ratio. It was also extended to definitions and equations for discernment versus recognition viewing and of the association between clear-air and cloudy visibility.

From the sensitive association of M vs V, which "filters through" all of the KM relations, it is concluded that observations or measurements of visibility can be employed to determine LWC values to accuracies unobtainable by any other (present) means. This has broad implications. For example, in the field of climatology, it would seem that statistical/contingency information and tables concerning visibility could be converted into corresponding tables of LWC to obtain operationally useful products; also that the LWC of natural clouds could be accurately assessed observationally. Moreover, it would appear that highly detailed predictions of size distribution, garnered from the sensitive M vs V relation, when combined compositely with other KM equations and with fall-velocity, turbulence, entrainment, and electric-field-gradient information, might contribute importantly to one of the current problems of prime Air force concern, namely that of the charge separation in clouds that causes hazardous lightning strokes. The sizes of the supercooled droplets in such clouds, especially in view of the distinct possibility that the largest and most unstable of the drops are likely to freeze first, must certainly have important consequences in charge separation. These are only a few of the possible applications that are foreseeable from exploitation of the KM association of M and V.

The equations of the report, since they have truncation terms, can be very useful in determining the capabilities and limitations of present cloud physics instruments and in developing compensation corrections where appropriate.

They can also be helpful in designing new instruments.

The development of the M vs Z equations for water clouds and aerosols—the first of their kind—should serve to reduce the error bounds in radar/lidar studies of clouds. Likewise, the information provided about the detectabilities of natural clouds may serve as a general reference and possibly be of interest to climatologists.

From the work of Appendix A, it is concluded that the composite relations and equations explained therein will

1. greatly simplify any future GL weather definition work of the SAMS/ABRES type or similar,
2. provide consistency and continuity information useful to the checking and development of storm models.

The Appendix A findings also suggest that the precipitation process in the atmosphere, from aerosols to the first initiation of the smallest cloud droplets to ultimate precipitation at the ground, proceeds as part of a "cascade" process, in which aerosols, with increasing relative humidity (rh) become cloud droplets, which, with further increases in rh, water-vapor deposition and coalescence, become rain drops, which, resulting from many growth factors, finally fall to the ground to complete the process. It is suggested that this "cascade analogy," as explained and illustrated in the appendix, could enhance our thinking about composite relationships across disciplinary boundaries.

Overall, the general conclusion to be derived from the total efforts of the present report is that the Khrgian-Mazin distribution function applied to cloud physics endeavors is highly versatile and extremely useful.

14. RECOMMENDATIONS

A number of suggestions and recommendations were made at various points of the text. Some of these will be reiterated and others advanced.

It is recommended, first of all, that consolidation efforts should be extended to insure the continuity and consistency of theoretical and empirical findings across the class boundaries of the many diverse fields of endeavor that are important to precipitation development in the atmosphere—from nuclei initiation to rain/snowfall completion. Extensive knowledge is available, but it is compartmented and requires quantitative consolidation.

With regard to visibility, which is a field in which any enhancement of accuracy will profitably affect all other fields, the obvious need was noted for a quantitative measure of "contrast"—gray-scale contrasts and color contrasts and combinations (which are the major factor that dominate visibility uncertainty). Such contrast information is undoubtedly available in the fields and literature of photonics, lithography, photography, human-visual-acuity, instrumental-vision-enhancement, camouflage, astronomy, satellite observations, architecture, etc. (For example, it might be mentioned that the minimum resolvable solid angle of the human eye is about $1/60°$ giving 3440 as the value of the constant of Eq. (123), which, in turn, from Eq. (124), yields a Koschmieder threshold-of-contrast value of $\epsilon_0 \cong 0.055$. It might additionally be mentioned that the determination of visibility by instrumental means will necessarily be highly involved in the general field of photonics with truncation effects considered.) Another factor of importance, dependent on the precise situation (such as viewing objects looking across a strongly-heated ground surface), is

that of atmospheric turbulence. This scintillation effect will tend to cause objects to appear "fuzzy" and will act to reduce contrast by aberrative reduction of resolution. A literature survey concerned with atmospheric visibility and conducted along the lines noted here should quickly enhance accuracy and lead to better visibility equations.

It was also suggested that theoretical efforts with Mie theory and atmospheric diffraction theory could reduce visibility uncertainty by providing better estimates of the extinction ratio for cloud droplets (also for aerosols and rain). This is recommended but it should be noted that there is a threshold level of minimum uncertainty, perhaps irreducible, that is associated with the secondary effects of multiple diffractions, internal reflections and scattering that may be impossible to quantify.

In radar meteorology, an obvious need exists for continuing the development of radars (probably in the K_u-Band) that can efficiently detect clouds and utilize various of the relations pointed out herein. Presently, few such radars are operationally available. They could contribute much. Research persons in the lidar field might profitably utilize certain of the equations developed herein, expecially that for the reflectivity factor. It is also concluded that the use of IR lidars for cloud studies will be difficult, since such lidars would operate in the Mie region.

As mentioned in the report, it is suggested that "visibility markers" should be devised and installed at synoptic and airway reporting sites. These would be markers designed specifically to provide constant, unchanging reference values of contrast and feature detail at carefully surveyed ranges (common or different) from the observing site(s). The accuracy of visibility reporting could be enhanced considerably by the use of such markers and the reports would become more "site specific" (as is important at airports), since the ranges and spacings of the markers (covering a 360° sweep of horizon) would establish the "representativeness resolution" of the observations and reports. This resolution is under our complete control.

Finally, it is recommended that some first approach sould be undertaken to "clean up" visibility terminology and symbology.

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Appendix A

Composite Distributions

During the SAMS/ABRES Program, after each missile launch or re-entry occurrence, AFGL provided predicted, tabulated values of the size distribution and number concentration of the hydrometeors that were likely to be present along the path courses of the vehicles. These efforts have been reported by Plank[6, 64, 66] (1974a, b and c), Barnes, Nelson and Metcalf[A1] (1974), Berthel[A2] (1976), Plank[1] (1977), Plank, Berthel and Barnes[19] (1980) and Plank and Berthel[2].

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(1982), and also in numerous informal AFGL reports documenting the specific missions, the so-called "60-day reports".

In these efforts, the end purpose was to provide the BMO (Ballistic Missile Office) with tabulations of estimated hydrometeor number-concentration and LWC over a size range of 1 to >5000 μm by altitude layers from the surface to the storm top. In 10 μm class widths, some 500 total linear classes would have been required to span the size range—a ridiculous number that would have provided good resolution for the cloud size-range of particles (in 20 classes) but would have been grossly excessive in the precipitation size-range (with >480 classes). Using 100 μm class widths, some 50 total classes would have been needed—still too many for practical tabulation and having the nasty consequence that the entire cloud size-range would have been documented in only 2 classes. To handle these problems, class widths were specified to increase in geometric progression from the smallest class to the largest. Ten classes were defined for the cloud size-range that spanned diameters from 0.8 to 80 μm (80 μm was the maximum detectable size of the JW instrument that provided the basic computational information.). The geometric spacing yielded eleven additional classes in the precipitation size-range covering diameters from 80 to 12,600 μm (diameters larger than the 5000 μm breakup size of rain were required to handle large snow aggregates). The tables for the BMO were thus held within reasonable size limits for report incorporation.

Another problem existed in trying to bridge the disciplines of cloud physics and precipitation physics. Much empirical data, in cloud physics, existed to show that a distribution function, such as the Khrgian-Mazin function discussed herein, provided a reasonable description for cloud sizes between about 1 μm and 100-200 μm. Overwhelming data existed, in precipitation physics, to show that rain (also snow) was well-described by a distribution function of exponential type (a zero-order Gamma function). The problem was that, when the separate distribution solutions for clouds and precipitation were "joined together" at a boundary in the drizzle size-range of hydrometeors, a discontinuity of number concentration, LWC and other quantities existed across the boundary in the tabulations. This discontinuity had serious consequences for the BMO users of our tables, since BMO was attempting to assess the "nose cone erosion" on re-entry vehicles moving through the storm hydrometeor environments. Hydrometeors with masses larger than a certain critical mass would "pass through" the bow-shock-wave to cause erosion. Those with smaller masses would not. The discontinuity in our tabulations occurred in the same approximate size (mass) range as that critical for the "onset of erosion". The problem was caused by a lack of consolidation between separate fields of endeavor.

It was recognized, at the time, that the separate distribution solutions could have been added together to eliminate the discontinuity. However, because of other operational pressures, such a technique was never developed for employment.

The previous comments indicate several of the problems that *we* encountered in *our* attempts to employ cloud-physics and precipitation-physics knowledge in a specific cross-disciplinary application. There are many other situations in the general field of aerosol/hydrometeor physics that require consolidation among the separate fields of aerosol, cloud, and precipitation physics. For example, in visibility forecasting, it is noticed that the atmosphere always contains aerosols with cross-sectional areas that, at one extreme, may impose such slight visibility reduction as to be regarded as negligible (unlimited, 30–100 miles or greater), but, at the other extreme, with large relative humidity and copious sources of pollutants and smoke (especially in topographical "basins"), the aerosol cross-sections may cause a large decrease of visibility, to a mile or so. Certainly,

then, aerosols cannot be ignored in visibility forecasting. Clouds also cannot be ignored, almost by definition, since they are the prime contributors to severe diminishment of visibility as discussed in Sections 6–9. Precipitation (rain and particularly snow) is likewise important to degraded visibility. Heavy rain, by itself, can impose visibility hazards to aircraft flight operations and automobile traffic. Snow can cause even more severe hazards. Visibility forecasting must, therefore, incorporate knowledge of the number concentrations and cross-sectional areas of aerosols, clouds, and precipitation, somehow consolidating the separate findings of the three fields of endeavor.

Within the confines of this appendix, it is only possible to outline the general nature of the distributions in the three disciplinary areas and to indicate how the distributions should appear with consolidation. Distribution functions, all of them Gamma functions, are presented in their final, applied form. The derivation details of the equations are not presented. Five figures have been constructed and are furnished at the end of the appendix. Figure A1 shows the distributions of number concentration for several situations th :: will be identified. Figure A2 is a companion diagram to Figure A1 that illustrates a particular composite distribution. Figure A3 reveals the distributions of projected cross-sectional area, as related to visibility. Figure A4 indicates the distributions of particle mass or LWC. Figure A5 depicts the distributions of the radar reflectivity factor. The scale limits of each figure span the minimum to maximum conditions likely to be encountered in the atmosphere that are important to various aspects of the three disciplines. It might be noted that the simple plotting of the distributions on common scales is highly revealing by itself. This *must* be approximately how the distribution totalities of aerosols/hydrometeors should appear, if we accept the careful, long-term findings of the numerous research persons in each of the fields.

A1. PERTINENT EQUATIONS

For *clouds*, the final equations based on the Khrgian-Mazin distribution function have been developed in the main text herein. The pertinent equations are numbers 41 and 60–74 (see pages 17, 26 and 27).

For *rain*, the final developed equations based on the exponential distribution function and the work of Plank[1] (1977) are presented below without extensive comment. The equations apply to rain of the Joss et al[63] (1968) widespread type (as normally observed in the AFGL/SAMS program). Also, since an exponential function has no modal peak (no maximum of N_D, except, in a sense, at $D = d$), the number concentration equations were written in terms of the "exponential slope" quantity Λ, and the liquid water content, M. The other equations are written in terms of the modal diameters D'_A, D'_M and D'_Z (plus M), and Λ is assumed to be determinable from measurements and M to be directly measurable. The distributions of A_D, M_D and Z_D do have maxima, hence their modal diameters are noted, expressed in terms of Λ. The equations relating the peak values of the distributed quantities N_{D_p}, A_{D_p}, M_{D_p}, and Z_{D_p} with the totals N, A, M, and Z are also provided, as is the visibility quantity $\forall$ (ref. Eqs. (40), (41), and (42) in Section 6.1). Except for r_A, the truncation ratios r_N, r_M, and r_Z, which differ from those for clouds, have been defined by Plank[1].

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Equations for Number Concentration

$$N_D = 7230\ M^{0.0185} e^{-2.18\, D\, M^{-0.250}} \qquad (d \le D \le D_m) \qquad \text{No. m}^{-3}\ \text{mm}^{-1}. \qquad \text{(A1)}$$

$$\Lambda = 2.18\ M^{-0.250} \qquad \text{mm}^{-1}. \qquad \text{(A2)}$$

(basic equation stemming from the M vs Z relation of Joss)

$$N = \frac{3320\ M^{0.264}\ r_N}{r_M} \qquad \text{No. m}^{-3}. \qquad \text{(A3)}$$

$$N_o = 7230\ M^{0.0185} \qquad \text{No. m}^{-3}\ \text{mm}^{-1}. \qquad \text{(A4)}$$

(N_o is the $D = 0$ intercept of N_D)

Equations for Projected Cross-Sectional Area

$$A_D = 5.68 \times 10^{-3}\ M^{0.0185}\ D^2\ e^{-2.18\, D\, M^{-0.250}} \qquad (d \le D \le D_m) \qquad \text{m}^{-1}\ \text{mm}^{-1}. \qquad \text{(A5)}$$

$$D'_A = 2/\Lambda = 0.917\ M^{0.250} \qquad \text{mm}. \qquad \text{(A6)}$$

$$A = \frac{1.10 \times 10^{-3}\ M^{0.768}\ r_A}{r_M} \qquad \text{m}^{-1}. \qquad \text{(A7)}$$

$$\forall = \frac{1}{A} = \frac{910\ M^{-0.768}\ r_M}{r_A} \qquad \text{m}. \qquad \text{(A8)}$$

$$A_{D_p} = 6.46 \times 10^{-4}\ M^{0.518} \qquad \text{m}^{-1}\ \text{mm}^{-1}. \qquad \text{(A9)}$$

Equations for Liquid Water Content

$$M_D = 3.79\ M^{0.0185}\ D^3\ e^{-2.18\, D\, M^{-0.250}} \qquad (d \le D \le D_m) \qquad \text{g m}^{-3}\ \text{mm}^{-1}. \qquad \text{(A10)}$$

$$D'_M = 3/\Lambda = 1.38\ M^{0.250} \qquad \text{mm}. \qquad \text{(A11)}$$

M is assumed to have been measured

$$M_{D_p} = 0.492\ M^{0.768} \qquad \text{g m}^{-3}\ \text{mm}^{-1}. \qquad \text{(A12)}$$

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[1] Plank, V.G. (1977) *Hydrometeor Data and Analytical-theoretical Investigations Pertaining to the SAMS Missile Flights of the 1972-73 Season at Wallops Island, Virginia. AFCRL/SAMS Report No. 5.* AFGL-TR-77-0149, AD A051 192, ERP No. 603, 239 pp.

Equations for Radar/Lidar Reflectivity Factor

$$Z_D = 7230\ M^{0.0185}\ D^6\ e^{-2.18\ D\ M^{-0.250}} \quad (d \le D \le D_m) \quad mm^6\ m^{-3}\ mm^{-1}. \quad (A13)$$

$$D'_Z = 6/\Lambda = 2.75\ M^{0.250} \quad mm. \quad (A14)$$

$$Z = \frac{22{,}200\ M^{1.77}\ r_Z}{r_M} \quad mm^6\ m^{-3}. \quad (A15)$$

$$Z_{D_p} = 7750\ M^{1.52} \quad mm^6\ m^{-3}\ mm^{-1}. \quad (A16)$$

For *aerosols*, the final developed equations based on the Diermendjian[14] (1964) distribution function are presented below. The equations express the distributed and totals quantities in terms of the modal diameter, D'_N, of the N_D distribution and the mass content, M, which are presumed to be measurable or deducible quantities. The equations for the modal diameters of the A_D, M_D, and Z_D distributions are also given. The equations relating the peak values of the distributed quantities N_{D_p}, A_{D_p}, M_{D_p}, and Z_{D_p} with the totals N, A, M, and Z are likewise provided, as is the visibility quantity $\forall$. The truncation ratios for aerosols, which differ from those for clouds and rain, are not defined herein but they are readily derived, with some time-consuming effort, or can be obtained from the author.

Equations for Number Concentration

$$N_D = \frac{3.18 \times 10^4\ M\ D^6\ e^{-6D/D'_N}}{D'^{10}_N} \quad (d \le D \le D_m) \quad No.\ m^{-3}\ mm^{-1}. \quad (A17)$$

D'_N is a constant that is assumed to be measurable mm. (A18)

$$N = \frac{81.8\ M\ r_N}{D'^3_N\ r_M} \quad No.\ m^{-3}. \quad (A19)$$

$$N_{D_p} = 2.02 \times 10^{20}\ M \quad No.\ m^{-3}\ mm^{-1}. \quad (A20)$$

Equations for Projected Cross-Sectional Area

$$A_D = \frac{0.0250\ M\ D^8\ e^{-6D/D'_N}}{D'^{10}_N} \quad (d \le D \le D_m) \quad m^{-1}\ mm^{-1}. \quad (A21)$$

$$D'_A = 1.33\ D'_N \quad mm. \quad (A22)$$

[14] Diermendjian, D. (1964) Scattering and polarization properties of water clouds and hazes in the visible and infrared. *Appl. Opt.* **3**:187–196

$$A = \frac{10^{-4}\, M\, r_A}{D'_N\, r_M} \qquad m^{-1}. \qquad \text{(A23)}$$

$$\forall = \frac{1}{A} = \frac{10^{4}\, D'_N\, r_M}{M\, r_A} \qquad m. \qquad \text{(A24)}$$

$$A_{D_p} = 1.31 \times 10^{5}\, M \qquad m^{-1}\, mm^{-1}. \qquad \text{(A25)}$$

Equations for Mass Content

$$M_D = \frac{16.7\, M\, D^{9}\, e^{-6D/D'_N}}{D'^{\,10}_N} \qquad (d \le D \le D_m) \qquad g\, m^{-3}\, mm^{-1}. \qquad \text{(A26)}$$

$$D'_M = 1.5\, D'_N \qquad mm. \qquad \text{(A27)}$$

M is assumed to be measurable $\qquad g\, m^{-3}$ (A28)

$$M_{D_p} = 3170\, M \qquad g\, m^{-3}\, mm^{-1}. \qquad \text{(A29)}$$

Equations for Radar/Lidar Reflectivity Factor

$$Z_D = \frac{3.18 \times 10^{4}\, M\, D^{12}\, e^{-6D/D'_N}}{D'^{\,10}_N} \qquad (d \le D \le D_m) \qquad mm^{6}\, m^{-3}\, mm^{-1}. \qquad \text{(A30)}$$

$$D'_Z = 2.00\, D'_N \qquad mm. \qquad \text{(A31)}$$

$$Z = \frac{1170\, M\, D'_N\, r_Z}{r_M} \qquad mm^{6}\, m^{-3}. \qquad \text{(A32)}$$

$$Z_{D_p} = 5.0 \times 10^{-7}\, M \qquad mm^{6}\, m^{-3}\, mm^{-1}. \qquad \text{(A33)}$$

A2. SPECIFIC EQUATION SOLUTIONS AND PLOTS

The equation sets (A17)-(A33), for aerosols, (60)-(74), for water clouds, and (A1)-(A16), for rain, are discussed below and illustrated in Figures A1-A5.

First, with regard to *aerosols*, the dry-rural and dry-tropospheric aerosol models reported by Fenn, et al[37] (Figures 18-10 and 18-12), indicate that the peak number concentration of the aerosols at 0% relative humidity is about $N_{D_p} = 1.3 \times 10^{5}\ cm^{-3}\ \mu m^{-1}$ ($= 1.3 \times 10^{14}\ m^{-3}\ mm^{-1}$). The

[37] Fenn, R.W., Clough, S.A., Gallery, W.O., Good, R.W., Kneizys, F.X., Mill, J.D., Rothman, L.S., Shettle, E.P., and Volz, F.E. (1985) Optical and Infrared Properties of the Atmosphere. Chap. 18 in *Handbook of Geophysics and the Space Environment*, Jursa, A.S., Ed., AFGL, 1-80, ADA 167000.

modal diameter is about $D'_N = .025\ \mu m$ (= 2.5×10^{-5} mm). These two pieces of information are sufficient to solve the Diermendjian[14] (1964) distribution function for aerosols and additionally solve all of the dependent equations [Eqs. (A17)-(A33) herein].

When the above values of N_{D_p} and D'_N are substituted into Eq. (A20), solved for N, and ignoring truncation,

$$N = 3.4 \times 10^9\ m^{-3}\ (= 3400\ cm^{-3}), \tag{A34}$$

which gives the total number concentration of the aerosols of a "dry model" between the diameter limits $0 \le D \le \infty$.

The mass content of these aerosols may be deduced from Eq. (A19). There results

$$M = 6.5 \times 10^{-7}\quad g\ m^{-3} \tag{A35}$$

which value carries an assumption that the density of the aerosols is, on the average, for all types of solid, liquid-chemical, and "fluffy" particles, approximately equal to that of water, that is, ρ_W = 1.0 g cm^{-3}.

The distribution of the number concentration of the aerosols with diameter is specified by Eq. (A17). A partial plot of the distribution is presented in Figure A1, under the section labeled aerosols and identified as "$\triangle\!\!\!\!1$". The distribution represents a "minimum condition" for the atmosphere. Values smaller than these would not normally be anticipated.

The total projected cross-sectional area of the aerosols is, from Equation A23,

$$A = 2.6 \times 10^{-6}\quad m^{-1}, \tag{A36}$$

and the visibility quantity is

$$\forall = \frac{1}{A} = 3.8 \times 10^5\ m = 240\ miles. \tag{A37}$$

The maximum recognition visibility is

$$V = \frac{\forall\ ln(1/\varepsilon)}{k_\sigma}\quad m, \tag{A38}$$

[reference Eq. (48)] which, if we assume optimum contrast conditions [$ln(1/\epsilon) = 1.0$] and an extinction coefficient of $K_\sigma = 2.0$, yields

$$V \cong 1.9 \times 10^5\ m \cong 120\ miles. \tag{A39}$$

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[14] Diermendjian, D. (1964) Scattering and polarization properties of water clouds and hazes in the visible and infrared. *Appl. Opt.* **3**:187–196

This is a large visibility. But it is quite consistent with the minimum concentration of the aerosols of the dry model. Such visibilities are common in the western United States, as in Wyoming, for example.

The distribution of the cross-sectional area of the aerosols with diameter is given by Eq. (A21). A partial plot of this equation is shown in Figure A3, in the aerosol section, also labeled "△1". [The distribution of visibility, in non-dimensional terms, could also be plotted. This fact is merely noted, though, since such plots would be superfluous.]

The distribution of aerosol mass content with diameter is described by Eq. (A26). A partial plot is furnished in Figure A4, identified by "△1".

The total radar/lidar reflectivity factor is, from Eq. (A32),

$$Z = 1.9 \times 10^{-17} \text{ mm}^6 \text{ m}^{-3} \ (= -169 \text{ dBZ}). \tag{A40}$$

A partial plot of the distribution of Z with D, from Eq. (A30), is presented in Figure A5, likewise symbolized by "△1".

It is postulated that the mass loadings of aerosols in the atmosphere under "smoggy" conditions (with generation from many industrial/automotive sources) might be several orders of magnitude greater than those of the dry model. In this regard, two mass loadings larger than minimum were assumed. The first was $M = 5 \times 10^{-6}$ g m $^{-3}$, the second was $M = 10^{-4}$ g m $^{-3}$. These assumed values were not selected arbitrarily. They were chosen to represent aerosol conditions that might be described as "moderate" and "severe", also to serve discursive and illustrative purposes vis-a-vis the *cloud* distributions to be presented.

For each of the mass contents cited above, and with D'_N assumed constant = 2.5×10^{-5} mm, the equation set (A17)-(A33) was solved in a manner analogous to that outlined above. The results were:

For $M = 5 \times 10^{-6}$ g m^{-3}, with plotting symbol "△2",

$N = 2.6 \times 10^{10}$	m^{-3}	$(= 26{,}000 \text{ cm}^{-3})$,
$A = 2.0 \times 10^{-5}$	m^{-1}	
$\forall = 5 \times 10^4$	m	(= 31 mi),
$V \cong 2.5 \times 10^4$	m	($\cong$ 15.5 mi),
$Z = 9.1 \times 10^{-17}$	$\text{mm}^6 \text{ m}^{-3}$	(= −160 dBZ),

For $M = 10^{-4}$ g m^{-3}, with plotting symbol "△3",

$N = 5.2 \times 10^{11}$	m^{-3}	$(= 520{,}000 \text{ cm}^{-3})$,
$A = 4.0 \times 10^{-4}$	m^{-1}	
$\forall = 2500$	m	(= 1.6 mi),
$V \cong 1250$	m	($\cong$ .80 mi),
$Z = 2.9 \times 10^{-6}$	$\text{mm}^6 \text{ m}^{-3}$	(= −55 dBZ).

Partial plots of the distribution equations (A17), (A21), (A26) and (A30) are shown in Figures A1-A5. Those for the "moderate" M value of 5×10^{-6} g m^{-3} are symbolized by "△2"; those for the "severe" M value of 10^{-4} g m^{-3} are identified by "△3".

Discussion of these aerosols results and plots will be withheld until the cloud distributions and rain distributions are also presented.

The distribution and totals equations for clouds were developed herein. The equation set, based on the distribution function of Khrgian and Mazin, is comprised of Eqs. (60)-(74). The format of the set is the same as that for aerosols. The cloud set of equations was solved for the three M values, $M = 10^{-4}$ g m^{-3} (light), and $M = 0.01$ g m^{-3} (moderate) and $M = 1.0$ g m^{-3} (heavy), with K_σ of Eq. (A38) assumed to be 1.5. The results are listed below.

For $M = 10^{-4}$ g m^{-3}, with plotting symbol "$\boxed{1}$".

$N = 4.43 \times 10^{7}$	m^{-3}	(= 44.3 cm^{-3}),
$A = 7.21 \times 10^{-5}$	m^{-1}	,
$\forall = 1.39 \times 10^{4}$	m	(= 8.6 miles),
$V \cong 9300$	m	($\cong$ 5.7 miles),
$Z = 4.62 \times 10^{-9}$	mm^{6} m^{-3}	(= −83 dBZ),

For $M = 0.01$ g m^{-3}, with plotting symbol "$\boxed{2}$".

$N = 1.06 \times 10^{8}$	m^{-3}	(= 106 cm^{-3}),
$A = 0.00208$	m^{-1}	,
$\forall = 48.1$	m	(= 0.300 mi = 1580 ft),
$V \cong 32$	m	($\cong$ 0.20 mi $\cong$ 1060 ft),
$Z = 1.93 \times 10^{-5}$	mm^{6} m^{-3}	(= −47 dBZ),

For $M = 1.0$ g m^{-3}, with plotting symbol "$\boxed{3}$".

$N = 2.55 \times 10^{8}$	m^{-3}	(= 255 cm^{-3}),
$A = 0.0600$	m^{-1}	,
$\forall = 16.7$	m	(= 54.7 ft),
$V \cong 11$	m	($\cong$ 36 ft),
$Z = 0.0803$	mm^{6} m^{-3}	(= −11 dBZ).

Partial plots of the distribution equations for clouds, Eqs. (60), (64), (68), and (71) are furnished in Figures A1-A5. They are symbolized as indicated in the headings of the listings above.

The equation set for *rain*, based on an exponential distribution function, is composed of Eqs. (A1)-(A16). The format of the set is analogous to those for aerosols and clouds, with the minor exception that Eq. (A2) contains the "exponential slope" quantity, Λ, rather than the modal diameter, D'_N, of the like equations of the other sets.

The distribution and totals equations of the rain set were evaluated for the three M values, $M = 0.1$ g m^{-3} (small), $M = 1.0$ g m^{-3} (moderate) and 10 g m^{-3} (large), with K_σ of Eq. (A38) assumed to be 1.0. Additionally, the rain rates, R, corresponding to the M values, were computed from the equation of Plank[66] (1974b) for rain of the Joss et al[63] widespread type, that is,

66. Plank, V.G. (1974) *A Summary of the Radar Equations and Measurement Techniques Used in the SAMS Rain Erosion Program at Wallops Island, Virginia. AFCRL/SAMS Report No. 1*, AFCRL-TR-74-0053, Special Report No. 172, 108 pp., AD 778 095.

63 Joss, J., Thames, J.C., and Waldvogel, A. (1968) The variation of raindrop size distributions at Locarno. *Proc. Internatl. Conf. on Cloud Physics*, Toronto, Amer. Meteor. Soc., Boston, 369.

$$R = 19.9\ M^{1.16} \quad \text{mm hr}^{-1} \tag{A41}$$

The rain-rate categories noted are from the Federal Meteorological Handbook (FMHB-1B).

The findings of these computations were,

For M = 0.1 g m^{-3}, with plotting symbol "①".

$N = 1810$	m^{-3}	$(= 1.81 \times 10^{-3}\ cm^{-3})$,
$A = 1.88 \times 10^{-4}$	m^{-1}	.
$\forall = 5530$	m	(= 3.31 mi),
$V \cong \forall$	m	
$Z = 377$	$mm^6\ m^{-3}$	(= 26 dBZ),
$R = 1.5$	$mm\ hr^{-1}$	(very light),

For M = 1.0 g m^{-3}, with plotting symbol "②".

$N = 3320$	m^{-3}	$(= 3.32 \times 10^{-3}\ cm^{-3})$,
$A = 1.10 \times 10^{-3}$	m^{-1}	.
$\forall = 909$	m	(= 0.565 mi = 2980 ft),
$V \cong \forall$	m	
$Z = 2.22 \times 10^{4}$	$mm^6\ m^{-3}$	(= 43 dBZ),
$R = 20$	$mm\ hr^{-1}$	(heavy),

For M = 10 g m^{-3}, with plotting symbol "③".

$N = 6100$	m^{-3}	$(= 6.10 \times 10^{-3}\ cm^{-3})$,
$A = 6.45 \times 10^{-3}$	m^{-1}	.
$\forall = 155$	m	(= 500 ft),
$V \cong \forall$	m	
$Z = 1.31 \times 10^{6}$	$mm^6\ m^{-3}$	(= 61 dBZ).
$R = 290$	$mm\ hr^{-1}$	(very intense).

A3. DESCRIPTION OF FIGURES

The approximate diameter limits of the aerosol particles, cloud droplets and rain drops are indicated in Figures A1-A5 by the horizontal arrows in the upper portions of the figures. There is appreciable diameter overlap between aerosols and clouds and between clouds and rain. Moreover, as indicated in Figure A1 at the upper left, there are entities, such as polar molecules [ionized clusters of water vapor molecules (or other clusters)] that exist in large number concentration at sizes smaller than conventionally considered to be aerosols.

The distribution plots specified in the previous section are shown plotted on common scales in the figures. Except for Figure A2, they extend across the full conceivable range of distribution values involved in any and all of the three fields of endeavor. This results in "gross overplots" in certain instances but also provides "thinking references" concerning present or future possibilities and problems.

The distributions plots are symbol-coded as △1, △2, and △3, for aerosols, as $\boxed{1}$, $\boxed{2}$, and $\boxed{3}$, for clouds and as ①, ②, and ③, for rain. The 1's signify conditions that, in each discipline, would be

regarded as small or "near minimum", the 2's indicate moderate conditions, and the 3's illustrate conditions that are large or "near maximum".

Two diameter scales have been drafted on each of the figures for reader convenience. The bottom scale gives diameter in mm; the upper provides it in μm. Two scales of the distributed quantities are likewise provided. The left hand scales show distribution per millimeter bandwidth (for precipitation physicists); those at the right show distribution per micrometer bandwidth (for cloud and aerosol physicists). Also, in Figures A1 and A2, the right hand scale gives No. cm^{-3}, rather than No. m^{-3}, as at left.

The arrows, pointing right from the "3" curves of the aerosol distributions indicate how the distributions should shift to the right with increases in the relative humidity (rh) of the atmosphere (reference Fenn, et al,[37] loc. cit., Figures 18-10, 18-11 and 18-12, for example). It is presumed that one hundred percent rh exists at the tips of the arrows, to a rough first approximation.

The black dots at the right hand ends of the 2 and 3 curves of the rain distributions indicate the diameter truncation of raindrops that occurs naturally at their breakup size of $D_m \cong 5$ mm ($\cong 5000\ \mu$m). [The 1 curve does not attain breakup size (for any $N_D \geq 0.1\ m^{-3}\ mm^{-1}$).] The matter of "breakup truncation" in rain and the necessity for compensation will be addressed in the following section.

The distribution of number concentration for each of the fields of endeavor are shown in Figure A1. The distributions of projected, cross-sectional area (A_D) are displayed in Figure A3. The distributions of mass/LWC (M_D) are presented in Figure A4 and the ones for radar/lidar reflectivity factor (Z_D) are indicated in Figure A5.

No attempt has been made to "connect" the aerosol, cloud and rain curves of Figures A1, A3, A4, and A5 as would result from the "adding together" (or consolidation) of the distributions for each. There are simply too many combinatorial possibilities that would cause the figures to become hopelessly confused, if such illustration were attempted. (Some of the possibilities will be indicated presently.) It may be noted, though, that, since the figures cited all have logarithmic plotting scales, the "connection segments" between plots resulting from addition are "short and abrupt". An example of a composite distribution resulting from the addition of the 2, $\boxed{2}$, and 2 curves (for moderate conditions overall) is provided in Figure A2. To be more specific, the composite distribution of Figure A2 is comprised of the sum of Eq. (A17) plus Eq. (60) plus Eq. (A1), as evaluated for the particular conditions noted in Section A2. It is seen, in comparison with Figure A1, that the "connection segments" resulting from addition are indeed "short and abrupt". They can be "mentally supplied" for any of the distribution plots, N_D, A_D, M_D, or Z_D, of Figures A1, A3, A4, and A5 respectively, for any combination of aerosol/cloud/rain interest of the reader's choice.

A4. DISCUSSION

The discussion of this section is organized to indicate some general considerations first. Then the specific equations for number concentration will be considered to be followed by equal consideration of the equations for projected, cross-sectional area (and visibility), for the equations of particulate mass content/liquid-water content (and rain), and for the equations for the radar/lidar reflectivity factor (and detectabilities).

It is assumed, with regard to the distribution plots shown in Figures A1, A3, and A4, that the curves may be referenced singly or in composite terms, (following the example of Figure A2) with the reader requested to supply the necessary "mental interconnections". This request arises from the infinity of possible interconnections of interest across the three disciplines. For example, just from the nine distribution curves displayed in Figure A3, there are nine possible unimodal distributions. For "added" or "composite" distributions, there are 18 possible, continuous, bi-modal distributions and 27 possible, continuous, tri-modal distributions. Thus, the total possibilities are 54. The same number of possibilities exist for the distribution curves in each of the figures A1, A4, and A5. However, in Figure A1, since the distributions for rain have no modes, we can only speak of unimodal distributions or, on summation, bi-modal distributions. The reader can now appreciate the author's request for indulgence. There are 216 possible combinations contained in the figures cited just for the three atmospheric states classified approximately as small, medium and large.

It is pertinent to emphasize that the possibilities cited above are quite real and do represent atmospheric situations of common or occasional occurrence. Aerosols are ever-present. Clouds (fogs) can exist without the presence of rain. Rain can exist by itself, without clouds, as at the ground below cloud base or between cloud decks aloft. The bi-modal distributions will result primarily from aerosols plus clouds or from clouds plus rain. Tri-modality involves all entities, with different degrees of contribution from each.

Truncation should also be discussed. As noted previously, two types of truncation are of concern. First, there is the truncation associated with natural atmospheric processes. The prime example of this is the natural truncation of our descriptor equations that occurs at the upper size limit for rain, when the rain drops attain their $D_m \cong 5$ mm breakup diameter. This upper-diameter truncation is illustrated by the black dots at the right hand sides of Figures A1-A5. The truncation is rather innocuous for distributed number concentration, N_D, but it progressively becomes more severe for the larger diameter moments of distribution A_D, M_D, and Z_D. The truncation effects on N_D may be neglected with little loss of description accuracy but the effects on A_D, M_D and especially Z_D should certainly be considered.

With regard to natural truncation involving the composite equations of this appendix, the summed distribution equations for aerosols, clouds and rain (if all are present in the given situation) may simply be integrated from D = 0 to $D = D_m$. Taking the lower limit as D = 0 results in negligible loss of accuracy and greatly simplifies the equations for the truncation ratios, which then become dependent on only the upper diameter limit D_m.

For situations in which aerosols and clouds exist without rain, the composite equations will be descriptive between D = 0 and a D_m that is recommended to be taken at the upper size limit that conventionally defines "drizzle," that is, $D_m = 0.2$ mm (200 μm). For situations in which aerosols are of negligible importance, such as for Z_D (Figure A5), and clouds and rain are the primary hydrometeors of interest, it is suggested that the descriptive and integration limits of $D = d = 10^{-4}$ mm (0.1 μm) and $D = D_m = 0.2$ mm (200 μm) are appropriate.

If these suggested size limits of descriptivity and integration are accepted, and if the composite equations are programmed for computer solution, the programming will be relatively simple. However, the reader can intuit that valuable computer time will be expended in computing equation values, in composite addition, that are insignificant relative to other values involved in the

addition. This excess expenditure of computer time can be minimized by specifying, in the program, a threshold level of interest (in the N_D, A_D, M_D, or Z_D values) below which computation is not permitted and a zero value is substituted.

The second type of truncation involves instruments—the interpretation of their data based on their size limitations of measurement, (reference Figures 1-3 and associated commentary), also concerning the planning and design of new instruments to meet particular objectives. With such truncation, a minimum size limit D = d and a maximum size limit $D = D_m$ will usually exist and the distributed and totals quantities will be confined between these limits. For composite distributions, such as herein, the problems of integrating between the definite limits $d \le D \le D_m$ and securing appropriate truncation ratios, where d and D_m will differ with the given instrument, are rather complex. But the problems *are solvable* and it is recommended that they *should be solved* as part of the specifications of any instrument offered for research purposes for commercial sale.

We proceed now to discuss Figure A1 and its companion, Figure A2. It is seen, from the composite distribution of Figure A2 (for moderate conditions overall) that the distribution is bimodal with modal peaks in the aerosol and cloud sections of the figure and that there is an inflection zone joining the cloud and rain sections. The modal peak of aerosol contribution is some 5 orders of magnitude larger than that for clouds and some 11 orders of magnitude larger than the inflection zone between clouds and rain. These huge differences and the general appearance of the distribution gives one the distinct impression, mentioned earlier, that, at least in terms of the number concentration of the hydrometeors decreasing as the hydrometeors grow to precipitation size, the rain development process of the atmosphere ("warm rain" specifically) occurs in a manner analogous to a series of waterfalls, or "a cascade". The impression is enhanced by the observation that, as relative humidity increases, the distribution portion for aerosols moves to the right, further into the figure portion for clouds. The distributed number concentrations of the cloud droplets with increased LWC (as can be seen from the $\boxed{1}$, $\boxed{2}$, and $\boxed{3}$ distributions of Figure A1) likewise move to the right, further into the figure portion for rain. The rain distributions, too, move right toward increasing drop diameters with increased LWC (Figure A1). The impression is that a reservoir of moist aerosols (condensation nuclei) exists that begins "spilling over" with increased relative humidity to form cloud droplets. The cloud droplets, in turn, grow larger with relative humidity (vapor deposition) and coalescence to form rain drops of precipitable size. With fall distance through an environment containing cloud droplets and other rain drops of various sizes, the rainfall population progressively grows to larger sizes with fall distance, due to collisions and coalescence, until it impinges on the ground to complete the overall process.

The essentials of this process have been known for many years. But the presentation of the empirical findings of three fields of endeavor illustrated at a common scale is perhaps new.

We turn next to a consideration of the Figure A3 distributions of projected, cross-sectional area as related to visibility. The figure shows that the modal peaks of A_D are about one order of magnitude larger than the corresponding ones for clouds and about 4 orders of magnitude larger than the corresponding ones for rain. However, since there is also an order of magnitude variability among the 1, 2, and 3 curves of each of the disciplines, one cannot tell, a-priori by mere inspection, which combinations of the curves cause large or small, or important or inconsequential, contributions to degraded visibility. In this regard, it is of interest to summarize the contributions of aerosols (a), clouds (C) and rain (R) to total summed A (no subscript), to maximum,

theoretical recognition-visibility, $\forall$ [reference Sections 6 and 6.1, and Eq. (41)] and to maximum, "actual" recognition-visibility, or "Trabert recognition visibility", V [reference Section 6.2 and Eq. (48)].

The equation for total A in this appendix section is given by

$$A = A_a + A_C + A_R \qquad m^{-1}; \tag{A42}$$

the equation for $\forall$ is given, analogous to Eq. (41), by

$$\forall = \frac{1}{A} \qquad m, \tag{A43}$$

and the equation for V is given by

$$V = \frac{\ln (1/\varepsilon)}{k_{\sigma_a} A_a + k_{\sigma_C} A_C + k_{\sigma_R} A_R} \qquad m, \tag{A44}$$

from Eq. (48) and Eq. (A42) above. It was previously assumed that the extinction ratios k_{σ_a}, k_{σ_C}, and k_{σ_R} had the respective values of 2.0, 1.5, and 1.0. It is now assumed additionally, for general discussion purposes, that the contrast conditions of our supposed viewing are "optimum", such that $\ln (1/\varepsilon) = 1.0$. With these assumptions, Eq. (A44) simplifies to

$$V = \frac{1}{2A_a + 1.5A_C + A_R} \qquad m, \qquad \text{(A44)}$$

and we are dealing only with the individual component values of A_a, A_C, and A_R. Depending on the given situation, these values [1] may all contribute importantly to visibility or [2] one or two may have zero values (rain may be absent or clouds may be absent or both) or [3] one or two may have insignificant values relative to the other(s).

Several examples of term contributions to visibility reduction may be provided that are related to the "1, 2, 3 situations" specified in Section A2 and that reference Eqs. (A42), (A43), and (A45). The first examples concern situations of relatively large visibility. The following provide examples of progressively decreasing visibility that can occur in different ways.

The largest visibilities occur, of course, when only dry aerosols are present in the atmosphere. The △1 situation of Eq (A36) indicates that $A_a = 2.6 \times 10^{-6}\,m^{-1}$ (with $A_C = A_R = 0$) such that $\forall = 240$ mi and V = 120 miles [from Eqs. (A42), (A43), and (A45)]. Consider next a "smog" situation with a moderate concentration of aerosols, △2, combined with light fog, $\boxed{1}$. For this combination, $A_a = 2.0 \times 10^{-5}\,m^{-1}$, $A_C = 7.2 \times 10^{-5}\,m^{-1}$ and $A_R = 0$ which yields $\forall = 6.8$ mi and V = 4.9 mi. Next, conjure a situation of very small visibility (as in a closed metropolitan valley) in which there is dense smog, △3 plus $\boxed{3}$, combined with moderate rain, 2. Here, $A_a = 4.0 \times 10^{-4}\,m^{-1}$, $A_C = 0.060\,m^{-1}$, $A_R = 1.1 \times 10^{-3}\,m^{-1}$, $\forall = 16$ m (52 ft) and V = 11 m (36 ft). This is a fairly dense smog caused primarily by the water fog and rain. Finally, postulate the existence of a microburst associated with thunderstorm activity. Further postulate that dense clouds and very intense rain exist in the downdraft of the microburst, $\boxed{3}$ plus 3, and that aerosols are of no importance to the visibility state within the microburst. Thus, $A_a = 0$, $A_C = 0.060\,m^{-1}$, $A_R = 6.5 \times 10^{-3}\,m^{-1}$, $\forall = 15$ m (49 ft) and V = 10 m (33 ft). This demonstrates a situation of another kind that yields small visibility.

The above examples should provide the reader with some appreciation of the possible combinations of aerosols, clouds, and rain that dictate his/her viewing conditions under various circumstances. It should also be emphasized that, in the examples cited, $\forall$ and V are the maximum *recognition* visibilities (of two types). To obtain the corresponding maximum *discernment* visibilities, the $\forall$ and V values above should be multiplied by 2.8 (reference page 57). Furthermore, maximum discernment or recognition visibility only implies that it is *possible* to discern or recognize objects within the range distances cited. The actual discernment or recognition of an object depends on the object size and the features of the object (reference Section 9.4).

We now move to a consideration of Figure A4, which presents the distributions of aerosol mass content and cloud/rain liquid water contents. It is observed from the figure that the modal peaks of distributed mass content for aerosols are some two orders of magnitude smaller than the corresponding (same number category) peaks for clouds and about 1.5 orders of magnitude smaller than the corresponding peaks for rain. This means that the mass contribution of aerosols to the summed, total mass content of composite distributions is relatively small. (This, of course, must be true, since the "1, 2, 3 situations" illustrated were originally specified in terms of M.)

The author sees little need for offering specific examples of composite quantities involving mass contents. The distributions are important, without question, but the applications are highly specific.

As an aside concerning the LWC of rain, it may be noted that LWC can be successfully determined at the ground surface by the measurement of the rain-rate, R. The equation is the reverse of Eq. (A41) for Joss et al. widespread rain, which is

$$M = 0.0756 \, R^{0.864} \qquad \text{g m}^{-3} \tag{A46}$$

with R in units of mm hr^{-1}. In the SAMS/ABRES program, we obtained the surface data points of M in this manner using Joss momentum disdrometers[68] [Joss, Thams and Waldvogel (1968)].

We finally consider the distributions of the radar/lidar reflectivity factor of Figure A5. The modal peaks of the distributions for aerosols are seen to be extremely small relative to the corresponding peaks for clouds (some nine orders of magnitude smaller, or 90 dBZ) and relative to the corresponding peaks for rain (some 15 orders of magnitude smaller, or 150 dBZ). Thus, the radar returns from aerosols are negligible compared to those for clouds and rain and the lidar returns are generally negligible except under particular conditions that have not been considered herein.* The designer of a lidar, however, might be interested in the possibility of detecting aerosols of normal atmospheric concentration. If so, the distributions of Figure A5 and the total Z values of pages 100-102 provide some information about the difficulties of the task. It is additionally observed from Figure A5 that the modal peaks for clouds are about three orders of magnitude (30 dBZ) smaller than the corresponding ones for rain. This is quite consistent with operational knowledge of the comparative radar returns from water clouds and rain. (Also see Table 8).

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*These are the conditions that would prevail near a generation source of aerosols, such as the smoke from an industrial smokestack. Smoke contains number concentrations of aerosols that are tremendously larger than any discussed herein and can be readily detected visually or by lidar.

[68] Atlas, D., Hardy, K.R., Glover, K.M., Katz, I., and Konrad, T.G. (1966) Tropopause detected by radar. *Science*, **153**:1110–1112.

It is helpful to summarize the different M vs Z relations for aerosols, clouds and rain. For dry aerosols, assuming no truncation and that $D'_N = 2.5 \times 10^{-5}$ mm (as previously discussed) the relation is

$$M = 5.5 \times 10^{10}\, Z \qquad \text{g m}^{-3}, \tag{A47}$$

from Eq. (A32). For moist aerosols with 100 percent relative humidity, assuming that the value of D'_N will increase to about 7×10^{-5} mm in accord with Figures A1 or A2, the relation should be something like

$$M \cong 2.5 \times 10^{9}\, Z \qquad \text{g m}^{-3}, \tag{A48}$$

likewise from Eq. (A32). Again, it should be mentioned that these relations for aerosols probably have no present utility except for design/thinking purposes.

The M vs Z relation for clouds was discussed in Section 10.1. Here rewritten for no truncation, it is

$$M = 4.02\, Z^{0.552} \qquad \text{g m}^{-3}, \tag{A49}$$

The relation for rain of the Joss widespread type is

$$M = 0.00314\, Z^{0.576} \qquad \text{g m}^{-3}, \tag{A50}$$

from Plank[66] (1974b).

The distribution curves for rain of Figure A5 provide a good reference base for discussing truncation effects and the truncation ratios. As mentioned, the black dots of the figure, at D = 5 mm, which is the approximate breakup diameter for raindrops, reveal that the Z_D values at the points are relatively large and have not decreased in value in the manner of the other figure plots. The points "hang in the air", so to speak. This is an immediate indication that the truncation ratios r_M and r_Z of Eq. (A15) cannot be ignored *a priori*. It may be stated that these ratios, for the ①, ②, and ③ situations of rain, have the values $r_M = 0.99995$ and $r_Z = 0.9994$, for the ① situation (small), $r_M = 0.993$ and $r_Z = 0.92$, for the ② situation (medium), and $r_M = 0.87$ and $r_Z = 0.40$, for the ③ situation (large). [These values were computed from Eqs. (G10) and (G15) of Plank[66] (1974b).] Thus, the r_Z/r_M ratios that enter Eq. (A15) to modify it from the non-truncated state have the respective ①, ②, and ③ values of 0.9994, 0.926 and 0.46. Only the last value, for situation ③ is of major importance. The others are trivial. The same may be said about the truncation ratios involved in M and A. Natural upper boundary truncation will never be a problem for the number concentration N.

With regard to the truncation of the composite equations for instrument evaluation or design purposes, the distribution equations for N_D, A_D, M_D, and Z_D for aerosols, clouds, and rain, can

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[66] Plank, V.G. (1974) *A Summary of the Radar Equations and Measurement Techniques Used in the SAMS Rain Erosion Program at Wallops Island, Virginia. AFCRL/SAMS Report No. 1*, AFCRL-TR-74-0053, Special Report No. 172, 108 pp., AD 778 095.

simply be added together and integrated by parts between any diameter limits that might be appropriate.

A5. CONCLUDING REMARKS

The results of the investigations of composite distribution equations of this appendix are seen to make reasonable sense relative to our prior knowledge and experiences with number concentrations, visibilities, liquid water contents, and the expected values of signal return from aerosols, warm clouds, and rain using radar or lidar. Thus, although there is certainly a long way to go to refine the detailed values of equation coefficients, exponents, and multipliers, it may be concluded that the consolidated equations herein certainly bound (or "ballpark") the values of the distributed and totals quantities, at the very least, and that they probably provide excellent description in most instances.

These conclusions lead to the suggestion that the development of an empirical descriptor model might be of value, certainly for applications such as weather definition.

To establish an empirical, or artificially intelligent, computer model to check on the continuity and internal hydrometeor consistency of other mesoscale and storm models, the author would recommend the addition of the distribution equations for aerosols, clouds, and rain and integration of all equations between the limits $0 \leq D \leq 5$ mm. This lends itself to simple programming but is costly in computer time. Such time can be conserved, though, by "thresholding" the values of the distributed quantities to minimum levels of interest below which computation is not permitted and zero values are substituted. Furthermore, in such a program, if the particular problem does not involve aerosols, or if clouds and/or rain are not involved, any of the three terms of the composite distribution function can be set to zero value and computation can be restricted to the remaining terms or term. No truncation ratios need be computed except for heavy rain, as was demonstrated above for the Z values.

The value of such an empirical "descriptor model", which would reflect the combined observational experience of a great many investigators over numerous years, is that it would provide a reference base of how the particulates in the atmosphere, or in clouds or warm storms, exist naturally under a variety of conditions. Thus, any operational forecast model for clouds or storms, in its internal predicted states of hydrometeor interactions, should not depart too wildly from the experience model. The particle number concentrations of the working, predictive model should not differ vastly from experience. The predicted internal visibilities should not be ridiculous. The liquid water contents should be reasonable and should not fall beyond the bounds of maximum observed values. The radar/lidar reflectivity factors should agree approximately with experience and the predictive model should, in any "real time" comparisons with actual radar/lidar measurements, perform satisfactorily.

The reader will note that this appendix and report are carefully confined to water hydrometeors. Only occasional reference was made to ice crystal clouds and snow. There are good reasons for this. First, regarding ice crystals, we have not yet obtained the necessary measurements of the size distribution of ice crystals of the various types (or the also necessary measurements of their equivalent melted diameters, which yields crystal mass) to be able to ascertain even the general nature of the distributions. Hence, without such knowledge, it is premature to attempt the speci-

fication of a descriptive distribution function. Second, regarding snow in its various aggregate forms, present surface measurements and aircraft measurements using PMS equipment indicate that snow can usually be described by a distribution function of exponential type (as in the case of rain). However, there is huge difficulty in obtaining the mass distribution of the snowflakes that corresponds to the size distribution. As attempted now, by so-called "ℓ to D conversion", where ℓ is a length measure of snowflake size and D is the equivalent melted diameter, there are uncertainties of intolerable amount, [reference Crane[A3] (1978)]. There is a "stonewall" that prohibits further progress in "snow physics" until we acquire instruments that provide direct measurements of particle mass. [One such aircraft instrument, an "M Meter", has been designed and laboratory tested by an AFGL team[A4] (Plank, 1987).]

The equations of this appendix are analogous to equations of state for aerosols, clouds, and rain. Particular processes will occur within these hydrometeor regimes. But they cannot be handled by the present model, since its equations have no developmental or dissipative terms.

A3. Crane, R.K. (1978) *Evaluation of Uncertainties in the Estimation of Hydrometeors Mass Concentrations Using Spandar Data and Aircraft Measurements*. Sci. Rep. No. 1. AFGL-TR-78-0118, AD A059223, 107 pp.

A4. Plank, V.G. (1987) The M-Meter (particle mass sensor and spectrometer). *Second Airborne Science Workshop*, Univ. of Miami, Miami, Florida, Feb. 3–6, 1987, 171–173.

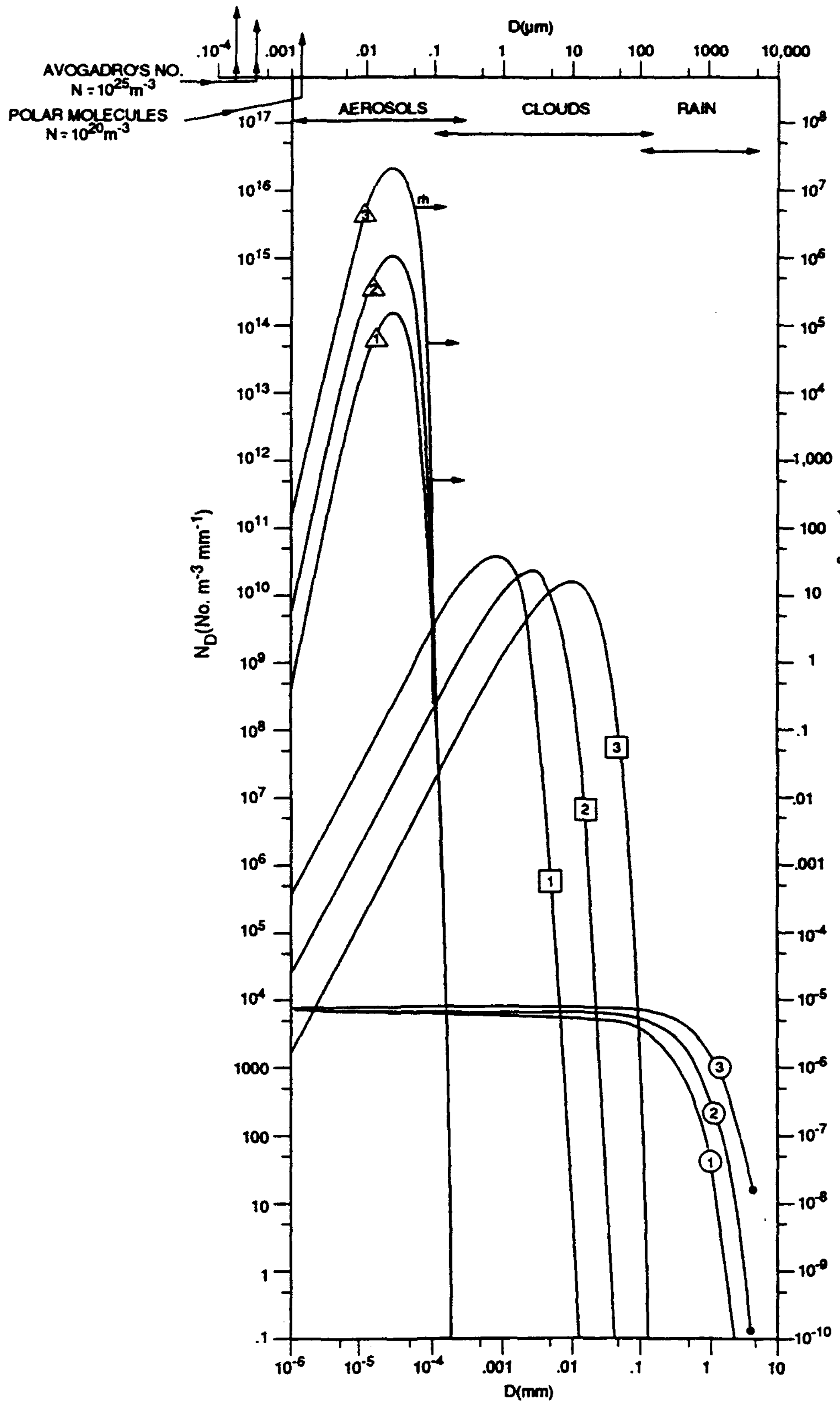

Figure A1. Distributions of number concentration for aerosols, clouds and rain—before their addition to become composite distributions, reference text

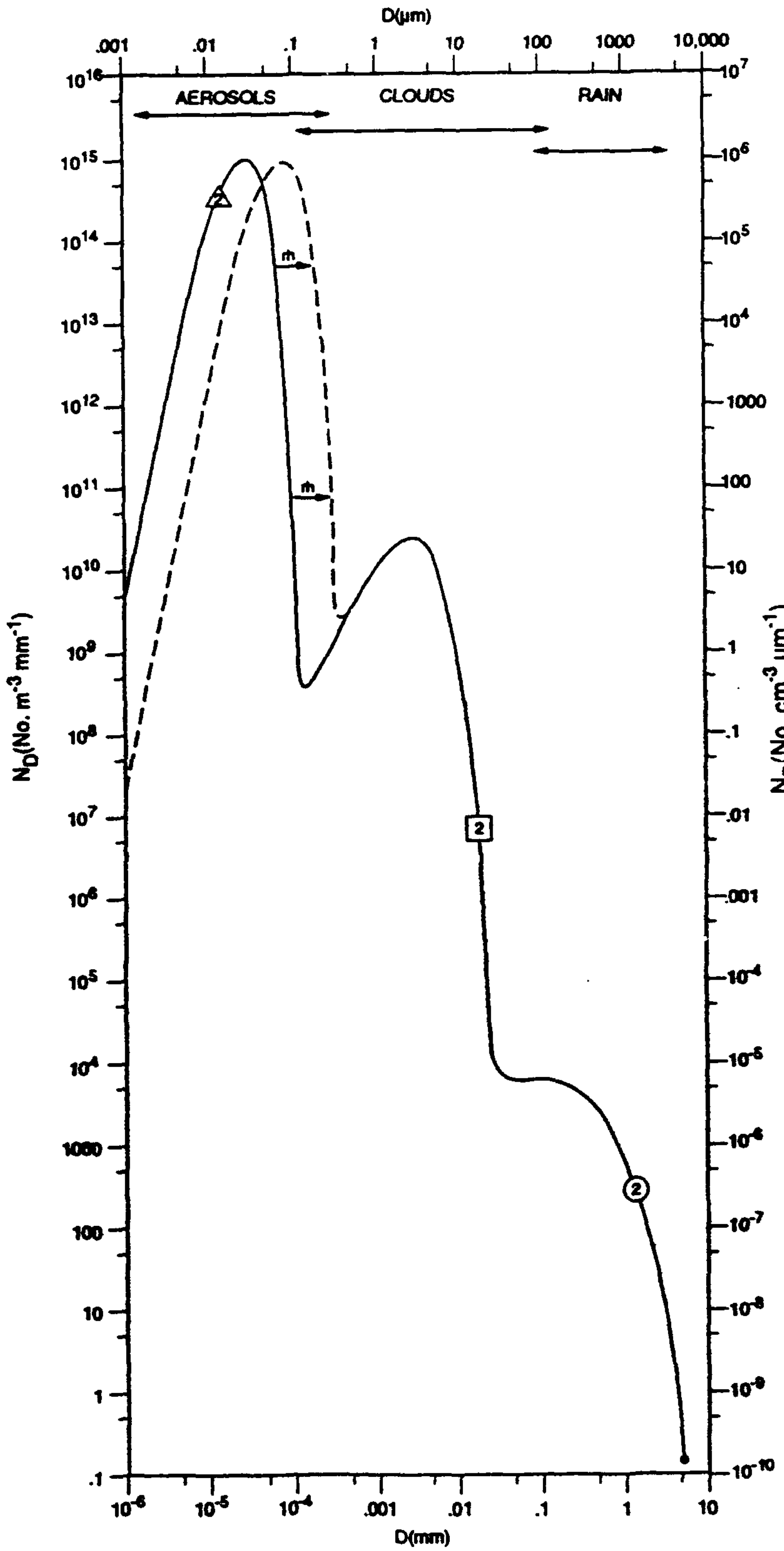

Figure A2. A companion diagram to Fig. A1 illustrating a case example of a summed, composite distribution of the number concentration of aerosols plus clouds plus rain, for moderate conditions. The dashed curve indicates the influence of atmospheric relative humidity (rh) on the distributed portion for aerosols. Reference text.

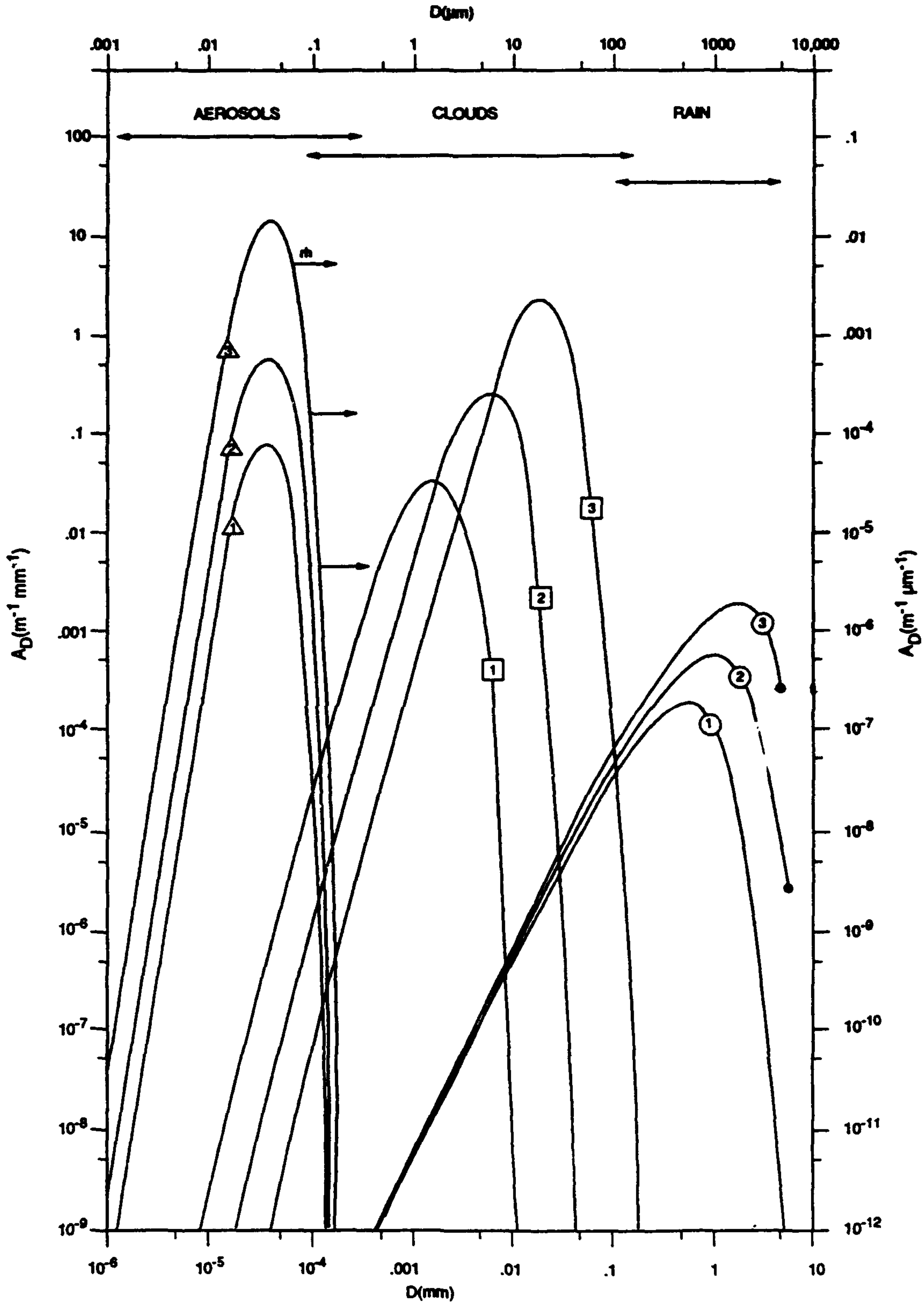

Figure A3. Distributions of projected, cross-sectional area for aerosols, clouds and rain—before their addition to become composite distributions, reference text

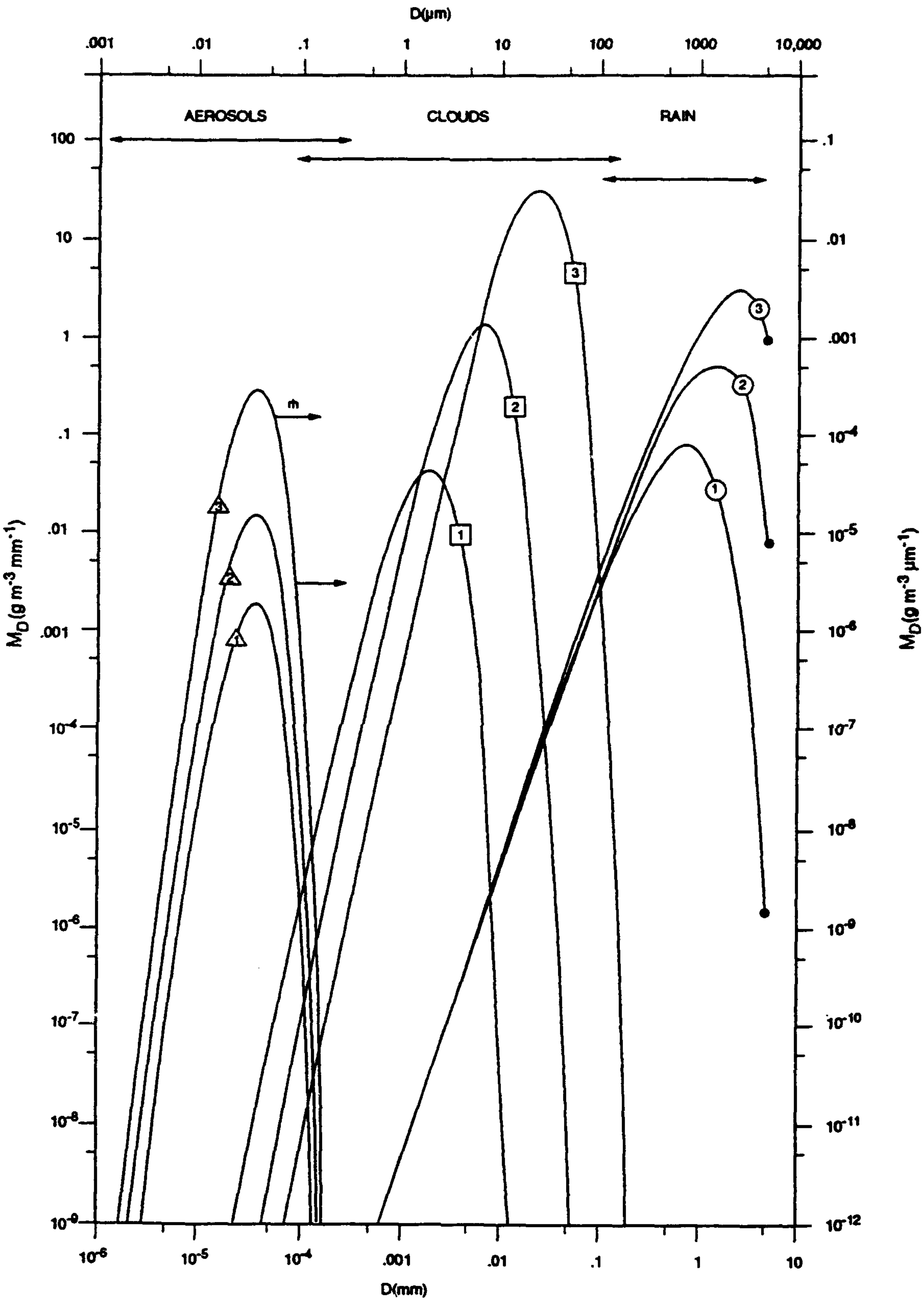

Figure A4. Distributions of mass/LWC for aerosols, clouds and rain—before their addition to become composite distributions, reference text

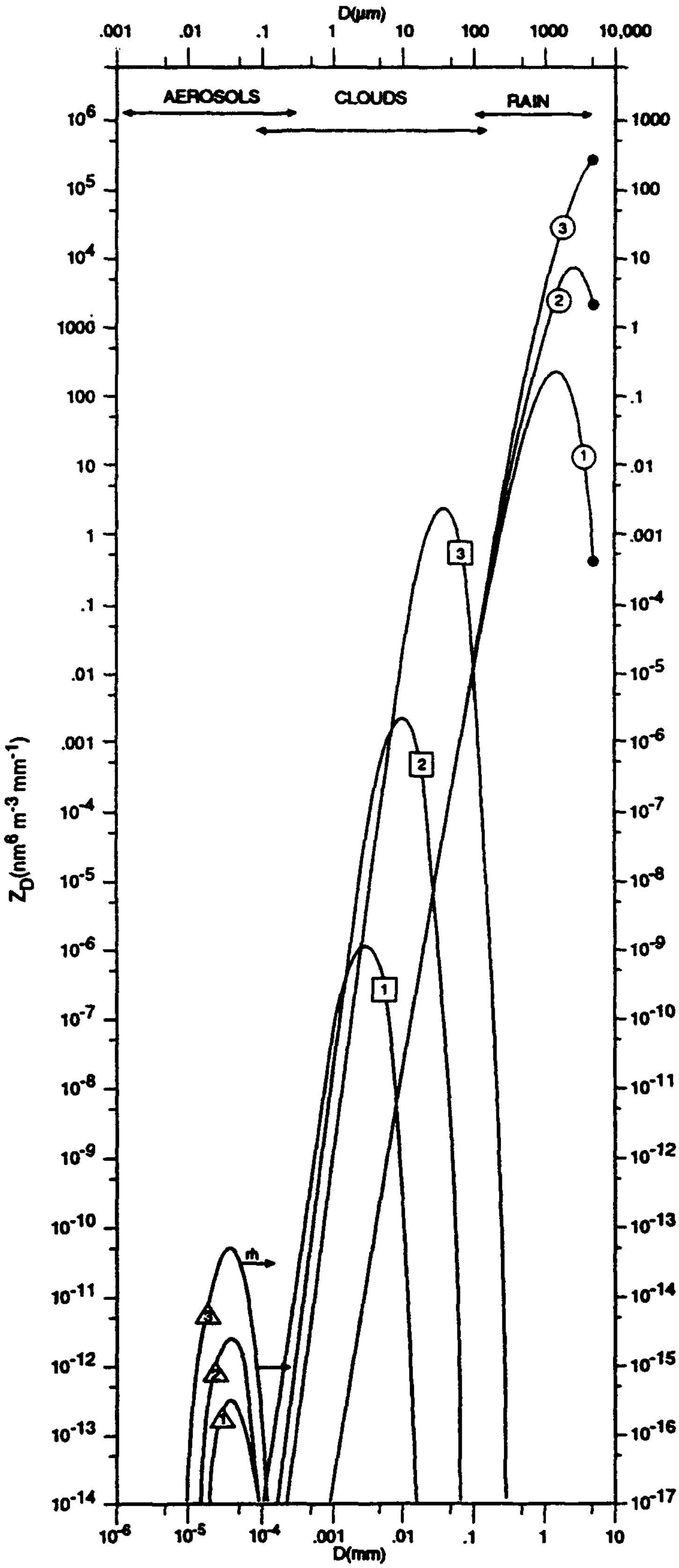

Figure A5. Distributions of radar/lidar reflectivity factor for aerosols, clouds and rain—before their addition to become composite distributions, reference text

Appendix B

The Mie Regions of Scattering and Diffraction as Related to th. ,ize-Distribution Spectra of Water Clouds Illuminated by Visible Light and X-Band Radar

One of the important factors in the weather-definition, visibility, radar/lidar, and other considerations of the main text, is the relation between (1) cloud droplet spectra illuminated and viewed at different radiative wavelengths and (2) the scattering/diffractive regions identified by Mie[18] (1908).

A few comments and an illustration are offered in this Appendix, which, hopefully, will shed some light on these relations. The comments and illustration are *indicative* only, for the author is well aware that the Mie theory is highly complex and cannot be summarized briefly. Also, the cloud-spectra-versus-Mie-theory relations are complicated and will merely be outlined herein. The emission and absorption lines of the gaseous constituents of the atmosphere add further complexities. These effects are beyond the scope of the report.

B1. THE MIE REGIONS OF SCATTERING/DIFFRACTION

Mie theory demonstrates that the ba.:k-scattering/diffractive cross section of an object depends, in general, on the object size, the dielectric properties of the material of which it is composed and (1) on the ratio of the size of the object to the wavelength of radiation and (2) on the ratio of the back-scattering cross section of the object (its "apparent size") to the actual cross-sectional area of the object (its real size).

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[18] Mie, G. (1908) Beiträge zur optik trüber medien, speziell kolloidaler metallosungen. *Ann. Phys.*, **25**:377–445 (Leipzig).

Stratton[26] (1941) accomplished the theoretical work that led to the presentation, by Kerr and Goldstein[27] (1951), of the summary diagram of Figure B1 (which the author has modified to express size in diameter terms, rather than radius). This diagram shows, for individual (subscripted "i") spherical objects—cloud droplets herein—the dependence of the extinction ratio k_σ on the ratio of droplet diameter to radiative wavelength (where $k_\sigma = \sigma/A$, that is, the extinction-cross-section of the droplets σ, divided by their cross-sectional area A). The three regions of the Mie theory are indicated: (1) the Rayleigh Region, which is important to radar investigation of water clouds, *also rain*, (2) the Mie Region, which is important in the "short microwave" and infrared portions of the radiative spectrum, as concerns water clouds and rain, and (3) the Region of Geometric Optics, where diffractive/reflective effects prevail, which are important to visibility and lidar considerations of clouds and rain.

The dashed line of Figure B1, is a plot of the "Rayleigh Law", that is,

$$k_{\sigma_i} = \frac{\sigma_i}{A_i} = \frac{k_{\sigma_i}}{\pi D^2} = 877 \left(\frac{D}{\lambda}\right)^4 \quad \text{N.D.,} \tag{B1}$$

which prevails in the region $D/\lambda \leq \sim 0.01$.

B2. CLOUD SIZE-RANGE AND D/λ VALUES FOR VISIBLE LIGHT AND X-BAND RADAR

In Section 7, page 25, a basic assumption was made and explained, namely that two "tie points" were established, the first specifying that the modal diameter, D'_N, of the Khrgian-Mazin distribution function, would be $D'_N = 10\ \mu m$ for a cloud liquid water content, $M = 1.0\ g\ m^{-3}$, and the second specifying that $D'_N = 1\ \mu m$, at the restricted/non-restricted visibility boundary of synoptic meteorology. This led to the $D'_N = 10\ M^{0.27}\ \mu m$ relation of Eq. (59). Moreover, in Section 9.4, page 57, the clear-air state of the atmosphere was specified to exist when the visibility was 30 miles, the LWC (or aerosol mass content) was $7.43 \times 10^{-5}\ g\ m^{-3}$ and the modal diameter, through Eq. (59), was 0.5 μm. The smallest drops or particles of the population will be smaller than the mode. A value of 0.2 μm is assumed, based on other work not reported. The maximum LWC observed in clouds is about 2-4 $g\ m^{-3}$, as noted previously. The modal diameter corresponding to $M = 4\ g\ m^{-3}$ is 14.5 μm, from Eq. (59). When maximum LWC exists, the *largest* droplets at the upper size end of the distributions will extend toward "large-drizzle" size, or about 200 μm. Thus, it is assumed that the diameters of primary concern for D/λ computations range from about 0.2 to 200 μm.

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[26] Stratton, J.A. (1941) *Electromagnetic Theory*. McGraw-Hill, 563 pp.

[27] Kerr, D.E., and Goldstein, H. (1951) Radar targets and echoes, *Propagation of Short Radio Waves*, **13**, Chap. 6, McGraw-Hill.

[15] Weast, R.C., and Astle, M.J., eds. (1982) *Handbook of Chemistry and Physics*. CRC Press, Inc., Boca Raton, Florida, A-63, E-202.

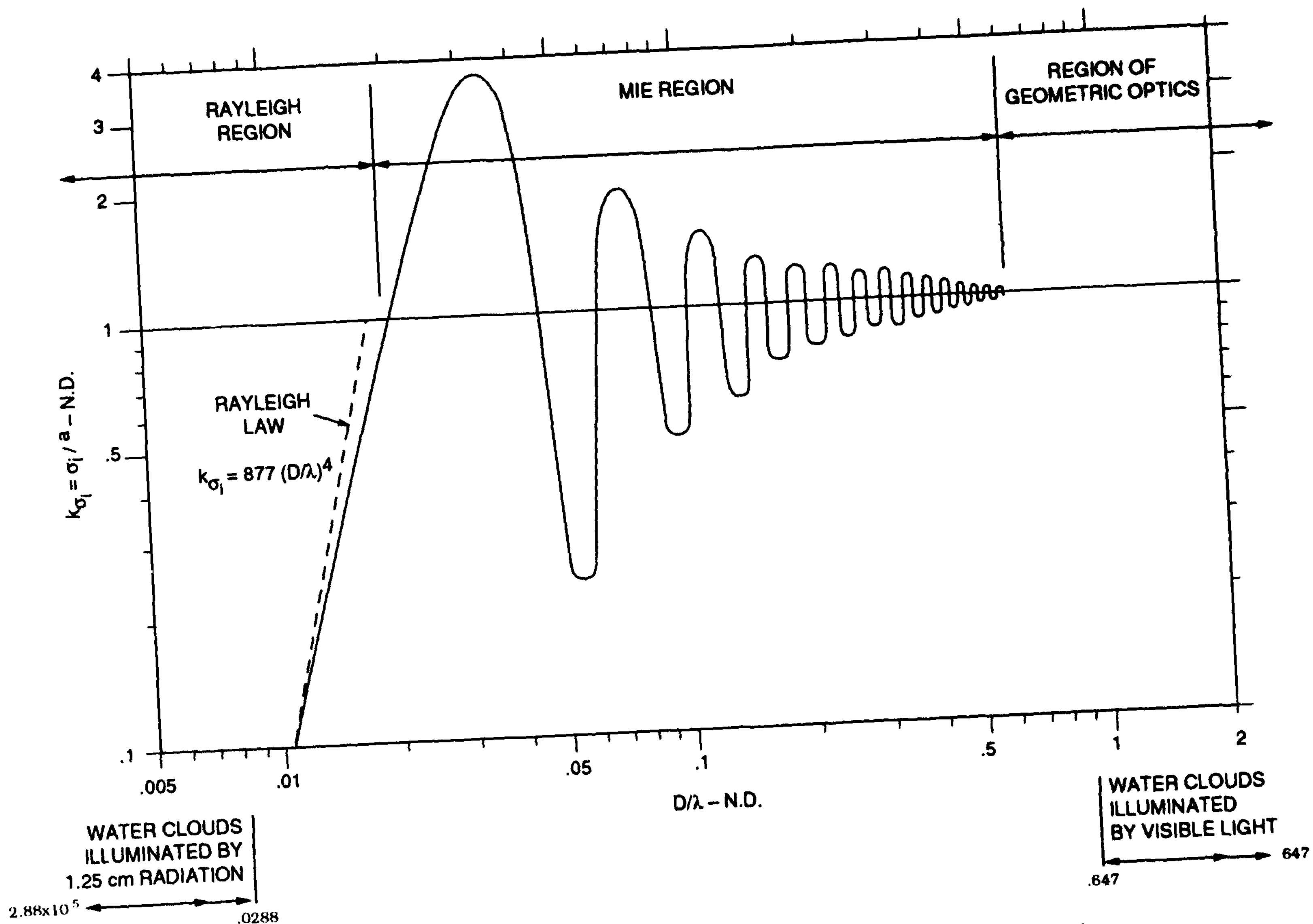

Figure B1. Illustration of Rayleigh Region, Mie Region and Region of Geometric Optics, from the theory of Mie (1908). The Rayleigh (1899) Law and equation are indicated. The D/λ limits are also indicated, below the graph, for water clouds in visible light and water clouds illuminated by X-Band radiation, λ = 1.25 cm. (Reference the text.)

Questions relative to the Mie theory now shift (still considering visibility) to the wavelength(s) of light that are predominantly involved in the processes of "human seeing". The processes are numerous but it is assumed herein that the wavelength of major importance is the wavelength of "maximum visibility", $\lambda = 0.556$ µm, as cited by Weast and Astle[15] (1982).

From the cloud diameters cited and the wavelength of light, just assumed, it follows that the D/λ values germane to the diagram of Figure B1 span the range

$$0.360 \leq D/\lambda \leq 360 \quad \text{N. D.}. \tag{B2}$$

This range is indicated at the bottom right of the figure by the horizontal line with arrows. The double arrows pointing right emphasize that the D/λ values extend beyond the diagram scale and "well into" the region of geometric optics. Thus, the extinction/scattering effects of water-clouds, involved in "visibility" and "visual-wavelength-lidar" are primarily diffractive/reflective, with contributions of unknown amount due to secondary and multiple diffraction, reflection, and scattering.

The volume reflectivity η and radar reflectivity factor Z were discussed in Section 10 and values from the KM equations were intercompared, for natural clouds, with the measurements of Plank, Atlas and Paulsen[73] (1955) and the equations of Atlas and Bartnoff[56] (1953). A vertical-pointing X-Band (now K_u-Band) radar, $\lambda = 1.25$ cm, was used to obtain the measurements and the comparison equations were solved for this same wavelength. The results are shown in Table 7.

For the range of cloud-droplet diameters to be anticipated in water clouds in the atmosphere, stated above, and $\lambda = 1.25$ cm,

$$2.88 \times 10^{-5} \leq D/\lambda \leq 0.0288 \quad \text{N. D.}. \tag{B3}$$

This range is noted in Figure B1, by the horizontal line with double arrows pointing left. The figure reveals that the D/λ values for X-Band radiation occur within the Rayleigh Region of the Mie theory with some of the largest, drizzle-size droplets being in the Mie region. Hence, water-clouds illuminated by radiation of 1.25 cm wavelength are primarily governed by the Rayleigh Law. [The particular application of the Rayleigh Law to water hydrometeors has been discussed by Mason[65] (1971). Mason's equation is Eq. (141) herein.]

B3. D/λ VALUES FOR WATER CLOUDS FOR OTHER RADIATIVE WAVELENGTHS

Additional comments are in order concerning the illumination of water clouds by radiative wavelengths other than the ones just described. In Table B1, the ranges of the D/λ ratios for water clouds are indicated in the last column, for radiative wavelengths spanning the ultraviolet

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[15] Weast, R.C., and Astle, M.J., eds. (1982) *Handbook of Chemistry and Physics*. CRC Press, Inc., Boca Raton, Florida, A-63, E-202.

[56] Atlas, D., and Bartnoff, S. (1953) Cloud visibility, radar reflectivity and drop-size distribution. *J. Meteorol.*, **10**:143–148.

[65] Mason, B.J. (1971) *The Physics of Clouds*, second edition. Clarendon Press, Oxford, England.

to the long-microwave portion of the spectrum. The particularly troublesome wavelengths—those involved in the oscillatory complexities of the Mie Region (0.02 $\leq D/\lambda \leq 0.7$)—are noted by asterisks. Such complexities are confined primarily to infrared and "short microwave" wavelengths and are especially severe (as can be seen comparing the D/λ values of the table with Figure B1) for wavelengths of about 0.00353–0.32 cm (35.3–3200 μm), or 94–8500 GHz (0.094–8.5 THz). A single asterisk in the table indicates moderate involvement with Mie scattering; a double asterisk denotes almost total involvement.

B4. COMMENTS

Since various references to aerosols (in the context of visibility) were made in the main text and Appendix A, it is of interest to note the D/λ ratios for these particles when illuminated by the wavelengths of Table B1. Aerosols exist in a wide range of diameter sizes ranging from about 10^{-5} to 10 μm. The modal peak of number concentration typically occurs at 0.01 μm. It may be stated that for UV, visible and IR illumination, the Mie Region is "crossed" by a portion of the size spectra of aerosols, thus adding complexity. For microwave radiation, aerosols lie entirely in the Rayleigh Region.

Table B1. D/λ ratios for water clouds illuminated by radiative wavelengths ranging from Ultraviolet to the long microwave. Asterisks indicate involvement in Mie scattering. The velocity of light, v, is 3×10^{10} cm s^{-1} = 3×10^{14} μm s^{-1} and frequency = v/λ.

Description of Illumination	Wavelength	Frequency	Range of Droplet-Diameter-to-Wavelength Ratios
Ultraviolet			
Solar Limit at Earth's Surface	0.292 μm	1030 THz	1.23 $\leq D/\lambda \leq$ 1230
Visible Light			
Blue	0.46 μm	650 THz	.783 $\leq D/\lambda \leq$ 783
Maximum Visibility	0.556 μm	540 THz	.647 $\leq D/\lambda \leq$ 647
Yellow	0.58 μm	520 THz	.621 $\leq D/\lambda \leq$ 621
Red	0.67 μm	450 THz	.537 $\leq D/\lambda \leq$ 537
Infrared			
* Terrestial Window	1 μm	300 THz	.360 $\leq D/\lambda \leq$ 360
* Typical Terrestial Outgoing	2 μm	150 THz	.180 $\leq D/\lambda \leq$ 180
** Commonly Used Wavelength	35.3 μm (.00353 cm)	8.5 THz (8500 GHz)	.0102 $\leq D/\lambda \leq$ 10.2
Microwave			
** W-Band	0.32 cm (3200 μm)	94 GHz (0.094 THz)	$1.13 \times 10^{-4} \leq D/\lambda \leq$ 0.113
*K_a-Band	0.86 cm	35 GHz	$4.19 \times 10^{-5} \leq D/\lambda \leq$ 0.0419
* K_u-Band (formerly part of X-Band)	1.25 cm	24 GHz	$2.88 \times 10^{-5} \leq D/\lambda \leq$ 0.0288
X-Band	3.2 cm	9.4 GHz	$1.13 \times 10^{-5} \leq D/\lambda \leq$ 0.0113
C-Band	6	5 GHz	$6.00 \times 10^{-6} \leq D/\lambda \leq$ 0.00600
S-Band	10 cm	3 GHz	$3.60 \times 10^{-6} \leq D/\lambda \leq$ 0.00360
L-Band	25 cm	1.2 GHz	$1.44 \times 10^{-6} \leq D/\lambda \leq$ 0.00144

Appendix C

Trabert's Equation for a Monodispersed Cloud Population and the Particular Solution of Stratton and Houghton

Many studies in the field of visibility have been based on the work of Stratton and Houghton[43] (1931), which used the concepts of Koschmieder[29, 30] (1924a, 1924b) and led to their particular modification of the equation of Trabert.[28]

The general form of Trabert's equation was not known at the time but it is convenient to use it as a discussion reference in this appendix. The equation, Eq. (48) of the main text, is

$$V = \frac{\ln(1/\epsilon)}{k_\sigma A} \quad \text{m,} \tag{C1}$$

where ϵ is the "contrast quantity", k_σ is the extinction ratio and A is the projected, cross-sectional area of the cloud droplets along the visibility path.

As mentioned in the main text, Trabert's equation can be made "distribution specific", if we have knowledge of A for any cloud size distribution of interest. Stratton and Houghton assumed a monodispersed distribution.

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[43] Stratton, J.A., and Houghton, H.G. (1931) A theoretical investigation of the transmission of light through fog. *Phys. Rev.*, **38**:159–165.

[29] Koschmieder, H. (1924) Theorie der horizontalen sichtweite. *Beiträge zur physik der freien atmosphäre*, **XII**:33–53.

[30] Koschmieder, H. (1924b) Theorie der horizontalen sichtweite II: kontrast und sichtweite. *Beitrage zur physik der freien atmosphare*, **XII**:171–181.

[28] Trabert, Wilhelm (1901) Die extinction des lichtes in einem truben medium (Schweite in wolken). *Meteor. Z.*, **18**:518–525.

C1. THE EQUATION FOR A MONODISPERSED CLOUD DISTRIBUTION AND THE CORRESPONDING TRABERT EQUATION

The development of this equation follows the development of Stratton and Houghton, as summarized succinctly by Aufm Kampe and Weickmann.[49]

The cross-sectional area of any single droplet of a monodispersed population, *for droplet radius in m*, is

$$a = \pi r^2 \qquad m^2. \tag{C2}$$

If there are N droplets per m^3 (assume a cube 1 m on a side) the summed, projected cross-sectional area of all droplets of the cube is

$$A = aN = \pi r^2 N \qquad m^{-1}. \tag{C3}$$

The volume of any single droplet is

$$v = \frac{4\ \pi r^3}{3}\ m^3, \tag{C4}$$

and its mass is

$$m = v\rho_w = \frac{4\pi r^3 \rho_w}{3} \qquad g, \tag{C5}$$

where ρ_w is the density of water.

For the N droplets of the cube, the total mass of all droplets, which is the liquid water content, M, is

$$M = m\ N = \frac{4\pi r^3 \rho_w N}{3} \qquad g\ m^{-3}. \tag{C6}$$

If N is eliminated between Eqs. (C3) and (C6),

$$A = \frac{3\ M}{4\rho_w r}\ m^{-1}. \tag{C7}$$

With ρ_w evaluated ($\rho_w = 10^6$ g m^3) and r expressed in μm, this becomes

$$A = \frac{3\ M}{4r} = \frac{0.75\ M}{r} \qquad m^{-1}. \tag{C8}$$

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[49] Aufm Kampe, H.J., and Weickmann, H.K. (1952) Trabert's formula and the determination of the water content in clouds. *J. Meteorol.*, **9**:167–171.

When Eq. (C8) is substituted into the Trabert equation (C1),

$$V = \frac{1.33\, r \ln(1/\epsilon)}{k_\sigma M} \ \text{m.} \tag{C9}$$

C2. THE STRATTON-HOUGHTON ASSUMPTIONS ABOUT ϵ AND k_σ AND THEIR FINAL VERSION OF TRABERT'S EQUATION

Koschmieder (loc. cit.) determined that the effect of contrast on visibility was governed by ln $(1/\epsilon)$, where ϵ is the "contrast quantity". He also determined that the threshold of contrast for a "black body" was given by $\epsilon = 0.02$, or $\ln(1/\epsilon) = 3.91$.

Stratton and Houghton assumed that the ϵ in Trabert's equation would have a constant value equal to Koschmieder's threshold value for a black body. With this assumption, Eq. (C9) became

$$V = \frac{5.2r}{k_\sigma M} \ \text{m.} \tag{C10}$$

Their last assumption, based on the work of Mie[18] (1908) and Debye[44] (1909), was that the extinction ratio had the value $k_\sigma = 2.0$, hence modifying Eq. (C10) to

$$V = \frac{2.6\, r}{M} \ \text{m}^{\dagger}. \tag{C11}$$

This is their final, modified version of the Trabert equation which appears as Eq. (82) of the main text and which was much employed in studies subsequent to Stratton and Houghton.

It is also of interest before closing to consider the question raised by Aufm Kampe and Weickmann[49] (1952), namely, "what is the effect of spectral broadening on the Trabert constant?". The development of the Trabert constant by Stratton and Houghton for a monodispersed distribution, as just demonstrated, may be compared directly with the "broader" Khrgian-Mazin distribution used in the visibility work of the present report. The procedure is the following.

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† Johnson[25] (1954) has pointed out that there is no justification for this last assumption.

25 Johnson, J.C. (1954) *Physical Meteorology*. New York Technical Press, MIT and Wiley, 393.

18 Mie, G. (1908) Beiträge zur optik trüber medien, speziell kolloidaler metallosungen. *Ann. Phys.*, **25**:377–445 (Leipzig).

44 Debye, P. (1909) Der lichtdruck auf kugeln von beliebigem material. *Ann. Physik*, **30**:57–136.

49 Aufm Kampe, H.J., and Weickmann, H.K. (1952) Trabert's formula and the determination of the water content in clouds. *J. Meteorol.*, **9**:167–171.

When, in the Khrgian-Mazin form of the general Trabert equation, Eq. (50) of the main text, the modal diameter, D'_N, is expressed in μm, rather than mm, and if a "modal radius", r'_N, is defined to replace the diameter, then Eq. (50), ignoring truncation, becomes

$$V = \frac{3.333 r'_N \ln (1/\epsilon)}{k_{a} M} \quad \text{m.} \tag{C12}$$

Since, for a monodispersed population, the r of Stratton-Houghton *is the mode*, that is,

$$r = r'_N \quad \mu\text{m}, \tag{C13}$$

this equation is directly comparable to their Eq. (C9) herein.

When the Koschmieder value of $\ln (1/\epsilon) = 3.91$ is assumed as it was by Stratton and Houghton, Eq. (C12) reduces to

$$V = \frac{13.0\, r'_N}{k_{a} M} \quad \text{m}, \tag{C14}$$

which is comparable to their Eq. (C10) herein.

Finally, also in accord with Stratton and Houghton, k_{a}, is assumed to have the value 2.0. Thus, Eq. (C14) converts to the Trabert equation,

$$V = \frac{6.5\, r'_N}{M} \quad \text{m}, \tag{C15}$$

with the Trabert constant,

$$C = 6.5 \quad \text{g m}^{-3} \quad \mu\text{m}^{-1}. \tag{C16}$$

This result certainly verifies the Aufm Kampe and Weickmann suspicion that spectral broadening leads to a larger value of the Trabert constant. They also mentioned that, with spectral broadening, the constant would tend to increase from 2.6 to the 5.8 value obtained and utilized by Richardson.[40] The work of the present report, based on the highly descriptive distribution function of Khrgian and Mazin, shows that the Richardson value is not only equaled, it is exceeded!

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[40] Richardson, L.F. (1919) Measurements of water in clouds. *Proc. Roy. Soc. London, A.* **96**:19–31.

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SUPPLEMENTARY

INFORMATION

AD A273810

Errata for Report PL-TR-91-2293 entitled

"IMPLICATIONS OF THE KHRGIAN-MAZIN DISTRIBUTION FUNCTION FOR WATER CLOUDS AND DISTRIBUTION CONSISTENCIES WITH AEROSOLS AND RAIN"

Due to the constraints of a terminating fiscal year with a potential loss of publication funds, a final proofreading of this report became impossible. Thus, the author agreed to having the report printed in the form existent on 15 September 1993 provided he would be permitted to write an errata and have it mailed post facto to the 1500, or so, institutions and persons on the distribution list. Such was agreed and the listing of residual report errors is presented herein.

Concerning errors in the figures, the units of the ordinate scale of Fig 7 should read M (gm^{-3}) , not M, (gm^{-3}) . The ordinate scale of Fig 17 should be gm^{-3} , not gm^3 ; the abscissa scale should read size, s (m) not size s, (m) . The second isoline from the bottom in the upper right diagram of the Fig 17 nomogram, which is presently unlabeled, should be labeled 5 . The abscissa scale of Fig 18 should be object size, s not object size s.

References, in the Table of Contents, to pps 103, 107, 108 and 114 should be to, instead, pps 98, 102, 103 and 109, respectively. Also, on pp iv, title of Appendix B, line 2, VISIBILE should be VISIBLE.

With regard to equations, the existing d'_N in Eqn 7 should read D'_N and the m of Eqn 57, requires replacement with M .

In the identification of references in the footnotes of the text, Ref 31, on page 22, should read 51: 427-449 , not 15: 427-449. Also, Ref 37, which should appear at the bottom of pp 103, is missing. However, it is included in the List of References.

Other errors in the text are as noted below:

Section	Page	Paragraph	Line(s)	Should Read
4	11	6	7-8	under the curves to the total areas under the curves
4	11	7	6	ratio of white to total areas shown visually
9.2	39	3	2	demonstrated
9.3	48	1	6	serendipitous
10.3	77	4	9	Missile
13	85	5	10	Air Force
A4	107	4	6	Joss, Thames, Waldvogel

Corrections to the Bibliography are: pp 161, 12th Reference, Levin, L.M.—should read—functions of cloud droplets. Pp 168, 10th Reference, Nyberg, A.—should read—Meddelander Communications. Pp 171, 14th Reference, Plank, V.G.—should be—AFCRL/SAMS. Pp 172, 12th Reference, line 1, Poljackova, E.A.—should be—Glavnaya. Pp 172, 12th Reference, line 2, Poljackova, E.A.—should be—Observatoria. Pp 177, 20th Reference, line 2, Selby, J.E.A.—should be—Supplement Code.